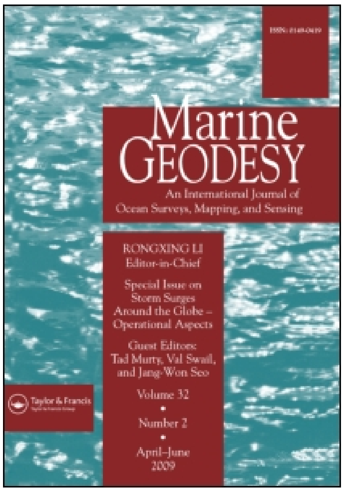

Marine Geodesy
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713657895

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Online publication date: 09 August 2010

To cite this Article Birkett, C. M. and Beckley, B.(2010) 'Investigating the Performance of the Jason-2/OSTM Radar Altimeter over Lakes and Reservoirs', Marine Geodesy, 33: 1, 204 — 238
To link to this Article: DOI: 10.1080/01490419.2010.488983
URL: http://dx.doi.org/10.1080/01490419.2010.488983

Marine Geodesy, 33(S1):204–238, 2010

ISSN: 0149-0419 print / 1521-060X online
DOI: 10.1080/01490419.2010.488983

Investigating the Performance of the Jason-2/OSTM Radar Altimeter over Lakes and Reservoirs

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Many inland water investigations utilize archival and near-real time radar altimetry data to enable observation of the variation in surface water level. A multialtimeter approach allows a more global outlook with improved spatial resolution, and combined long-term observations improve statistical analyses. Central to all programs is a performance assessment of each instrument. Here, we focus on data quantity and quality pertaining to the Poseidon-3 radar altimeter onboard the Jason-2/OSTM satellite. Utilizing an interim data set (IGDR), studies show that the new on-board DIODE/median and DIODE/DEM tracking modes are performing well, acquiring and maintaining the majority of lake and reservoir surfaces in varying terrains. The 20-Hz along-track resolution of the data, and particularly the availability of the range output from the ice-retracker algorithm, also improves the number of valid height measurements. Based on test-case lakes and reservoirs, output from the ice-retracker algorithm is also seen to have a clear advantage over the ocean-retracker having better height stability across calm and icy surfaces, a greater ability to gain coastline waters, and less sensitivity to loss of water surface when there is island contamination in the radar echo. Such on-board tracking and postprocessing retracking enables the lake waters to be quickly gained after coastline crossing. Values can range from <0.1 s to 2.5 s, but the majority of measurements are obtained in less than 0.4 s or <2.3 km from the coast. Validation exercises reveal that targets of ∼150 km^2 surface area and ∼0.8 km width are able to be monitored offering greater potential to acquire lakes in the 100–300 km^2 size-category. Time series of height variations are also found to be accurate to ∼3 to 33 cm rms depending on target size and the presence of winter ice. These findings are an improvement over the IGDR/GDR results from the predecessor Jason-1 and TOPEX/Poseidon missions and can satisfy the accuracy requirements of both the science-related and operational lake study programs.

Keywords Jason-2/OSTM, satellite radar altimetry, instrument performance, lakes, reservoirs

Introduction

Background

Many excellent in situ hydrologic monitoring networks are currently in operation measuring lake and river stage, the height of the water surface with respect to a datum. They do so often on an hourly or twice-daily basis to centimeter accuracy, and advanced systems have the

Received 24 December 2009; accepted 12 March 2010.
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additional capability to transmit their readings in near-real time. However, access to some gauge data can be restricted or delayed, and there are many remote regions where gauges cannot be deployed (Alsdorf et al. 2003). Recent reports have highlighted a continuing net loss of recording stations (Vörösmarty et al. 2001). This issue is a prime concern regarding both the human dimension and earth system issues relating to freshwater.

Major advances in the application of satellite radar altimetry have proved the ability to determine surface water height for some of the largest rivers, wetlands, and lakes around the world. The technique has been explored, validated, and applied in a number of test case regions (see reviews in Mertes et al. 2004; Birkett et al. 2005; Crétaux and Birkett 2006). The data are also employed in several operational type programs delivering surface level products for large inland water bodies (Birkett et al. 2009; Crétaux et al. 2009; Berry and Wheeler 2009, see appendix). In these programs the data are a mix of near-real time and archival measurements spanning almost two decades and derived from a number of differing agency instruments. Contributions to surface water measurement have also come from interferometric synthetic aperture radar (SAR) (Alsdorf et al. 2001) and from satellite laser altimetry (Harding and Jasinski 2004; Calmant et al. 2004; Birkett et al. 2005). In response to demand (Alsdorf et al. 2007), there is also a proposed ocean and inland water inter-agency mission, Surface Water Ocean Topography (SWOT). Based on wide-swath interferometry techniques it has been proposed for launch in the 2015 timeframe (Fu 2003; NRC 2007).

The continuation and advancement of these remote-sensing instruments will serve a variety of applications, including the assessment and management of water resources and the monitoring and prediction of droughts and floods. The determination of surface water balance is also critical in understanding land/ocean and land/atmosphere interactions. The role of rivers, wetlands, and lakes with respect to the transport of nutrients and as basin storage devices are also of prime importance. Climate change effects contribute to the uncertainty of all of these issues making the determination of hydrological parameters such as river discharge and volume storage critical. The contribution of altimetric height is central to both variables and can serve to support the current ground-based networks in this capacity.

The USDA GRLM Program

The ability to accurately record the changing water levels in the world's largest lakes and reservoirs via satellite radar altimetry has led to the implementation of several operational-based programs. One such program is sponsored by the U.S. Department of Agriculture Foreign Agricultural Service (USDA/FAS) and the National Aeronautic and Space Administration (NASA). In the current phase, the program utilizes data from the NASA/Centre National d'Etudes Spatiales (CNES) suite of altimeters, TOPEX/Poseidon (T/P), Jason-1, Jason-2/OSTM, as well as the U.S. Naval Research Laboratory's (NRL) GFO radar altimeter. The 2010 phase will also see data from the European Space Agency's (ESA) ERS and ENVISAT altimeters being incorporated. The associated lake-level products are derived from near-real time data (1–3 days after satellite overpass) and are used to observe high-water and long-term drought status, and for irrigation and crop production analysis.

Since the start of operations in 2003, the Global Reservoir and Lake Monitor (GRLM) program has output time series (post 1992) of level variations in the public domain for ~70 lakes and reservoirs around the globe. These numbers will greatly expand to ~500 in 2010 via the inclusion of ERS/ENVISAT. While the T/P, Jason-1 and Jason-2/OSTM missions have followed each other in succession, in the same 10-day repeat cycle orbit, there are variations in primary and auxiliary instruments and within the data processing. It is therefore essential that each instrument be assessed in terms of overall performance, checking both data quality and quantity and assuring that the accuracy satisfies the requirements of the USDA, the general public, and the science communities. The main objective of this study then is to assess the tracking performance of the Poseidon-3 radar altimeter onboard the Jason-2/OSTM satellite and to do so over a selection of targets of variable width, surface roughness, and surrounding terrain. An assessment of one of the altimetric parameter data sets is performed here, on-board tracking modes and postprocessing algorithm output are investigated, and surface water level time series are derived and validated. A summary of these preliminary results are presented and compared to historical missions. Successes and limitations are discussed with relevance to the GRLM and others science investigations.

Satellite Radar Altimetry

Full details of the principles of satellite radar altimetry can be found elsewhere (Fu and Cazenave 2001; Chelton et al. 2001) and specifically its application to inland water in a number of texts (e.g., Birkett 1995; Birkett 1998). In brief, the technique relies on the emission and reception of a microwave pulse that is transmitted to the surface from a nadir-pointing antenna. The timing of the echo allows the distance to the surface (or "range") to be estimated. Combining the range with knowledge of the satellite's altitude and applying a number of instrument-related and geophysical corrections lead to the derivation of the surface height with respect to a reference datum. With a defined orbit, altimetric satellites fly over a given surface point with a regular repeat period, currently ∼10, 17, or 35 days. With continuous operation the instrument has the potential to record surface height variations along each ground track and over the lifetime of the mission. The advantages to such a system include day/night and all-weather capability with little hindrance due to canopy or vegetation cover. Limitations include the ability to only record measurements at nadir, that is, along the ground tracks, and so lack the true global coverage of an imaging device. The ability to acquire and maintain "lock" on a surface, that is, the ability to identify the lake/reservoir echo response, select it for observation, and continue to monitor the water surface between the coastlines, will primarily be dependant on the instrument tracking logic. Within complex terrains and at the water/land boundaries data postprocessing methods can also improve target detection and the quantity of height retrievals.

A number of satellites have been launched with radar altimeters as part of their payload: Seasat (1978), Geosat (1986–1989), ERS-1 and -2 (1991–present), TOPEX/Poseidon (1992–2002), GFO (2000–2008), ENVISAT (2002–present), Jason-1 (2002–present), and Jason-2/OSTM (launched in June 2008). The science objectives have focused primarily on ocean observations though the ERS and ENVISAT altimeters, with their more complex surface tracking capabilities, were designed with more interdisciplinary aims that additionally focused on ice, land, and inland water. The degree of success over lakes and reservoirs is variable according to instrument, terrain complexity, surface roughness (wave height or freeze/thaw status), and the extent of water along the ground track that is presented to the instrument. Based on TOPEX/Poseidon measurements, for example, inland seas (e.g., Aral) and large lakes (e.g., Great Lakes, USA) can have time series of surface height measurements better than 5 cm root mean square (rms) accuracy when compared to gauge data. This can degrade to ∼10–20 cm for more sheltered, smaller lakes (e.g., Lake Chad, Africa) or many tens of centimeters to meters (e.g., Lake Powell, USA) for overpasses crossing narrow sections of water that are situated in mountainous terrain (Morris and Gill 1994; Birkett 1995; Ponchaut and Cazenave 1998).

Data and Methodology

The OSTM Mission

The Jason-2 Ocean Surface Topography Mission (Jason-2/OSTM) satellite was launched on June 20, 2008. It is the follow-on mission to the NASA/CNES Jason-1 satellite (2002–2008, carrying the Poseidon-2 radar altimeter) and to the NASA/CNES T/P mission (1992–2002, carrying both the NASA radar altimeter ALT, and the prototype solid state altimeter, SSALT or Poseidon-1). After launch, Jason-2/OSTM was placed in the same 10-day repeat orbit as its predecessors. From July 4, 2008, Jason-2/OSTM trailed behind Jason-1 by only 55 s, and they were held in this tandem configuration for cross-calibration purposes until January 26, 2009. After this period, Jason-1 was maneuvered into a new position where its ground tracks interleaved with those of Jason-2/OSTM with a 5-day phase lag. At the time of writing both satellites continue to operate from these orbits.

The Jason-2/OSTM mission is designed to serve the global ocean surface community particularly within an operational framework. In this respect NASA and CNES partnered with the National Oceanic and Atmospheric Administration (NOAA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The science requirements for the Jason-2/OSTM solid-state radar altimeter, Poseidon-3, aim at 1-Hz globally averaged sea surface heights accurate to 3.4 cm rms or better. These measurements combined with a high level of data processing will push the final goal to 2.5 cm rms (Dumont et al. 2009). Over inland water, this new mission is expected to offer at least the same performance as T/P and Jason-1. Note that in an effort to improve ocean data for Jason-1, many radar echoes over the smaller lakes and rivers were inadvertently rejected onboard, and so limited inland water data was downloaded and archived by the data processing centers (Birkett et al. 2009; Crétaux et al. 2009).

Poseidon-3 is derived from the heritage of the two-frequency Poseidon-2 altimeter (Carayon et al. 2003) and the SIRAL altimeter onboard CRYOSAT-1 and -2 (Wingham et al. 2006). It operates at 13.575-GHz (Ku-band) and 5.3-GHz (C-band) at an orbital altitude of $\sim$1336 km and has global coverage extending to $\pm 66^\circ$ latitude. During one orbital repeat period (i.e., one cycle $\sim$9.9 days) a total of 254 ascending and descending passes are made over the Earth's surface. Each repeat-pass has an associated ground track where the same location on the surface is revisited within a margin of $\pm$1 km. The cross-track separation at the equator is 315 km. The microwave energy returned to the antenna is captured within a given time (or range) window and sampled in the Fourier domain. The resulting waveform (the distribution of power within the range window) for Poseidon-3 comprises 128 independent range samples across a 60 m window. To avoid wrap-around effects, the leading and trailing range bins are trimmed and the ground processing focuses on waveforms that contain 104 independent range samples (compared to Jason-1 and T/P compressed waveforms of 64 range bins). The derived altimeter range measurements are provided within the IGDR at a rate of 1- or 20-Hz, that is, along-track averages over distances of 5.8 km or 290 m, respectively. They are derived with respect to the same datum as used by the T/P and Jason-1 mission, a reference ellipsoid having equatorial radius of 6378.1363 km and a flattening coefficient 1/298.257.

In addition to the altimeter, the Jason-2/OSTM satellite carries an Advanced Microwave Radiometer (AMR) to measure the wet tropospheric path delay on the altimeter range. This nadir-pointing instrument measures brightness temp at 18.7, 23.8 (primary channel), and 34.0-GHz. As per the radiometer on board Jason-1 (the JMR), the AMR employs three noise diodes for operational gain calibration to maintain stability, and to detect and correct for, jumps and drifts in the path delay record. This relieves the need for a cold sky calibration horn. The AMR reflector though is larger, ~1m, which nearly doubles the spatial resolution and the instrument is expected to provide reliable path delay measurements to within 15–20 km from the coast (Dumont et al. 2009). The Jason-2/OSTM mission also employs three techniques to calculate the satellite location and orbital altitude: the Doppler Orbitography and Radiopositioning Integrated by Satellite system (DORIS, the primary system), the Satellite Laser Ranging (SLR) hardware, and the Global Positioning System (GPS). The updated DORIS system includes an 8-beacon receiving capability and has an onboard real time function called DIODE (Détermination Immédiate d'Orbite par DORIS Embarqué) to compute the orbit ephemeris.

To assist with coastal and inland water programs new tracking modes have been implemented into the Poseidon-3 operating strategy and two of these make use of the DORIS/DIODE onboard navigation loop which gives the instantaneous satellite altitude to ~10 cm accuracy. The overall aim is to reacquire the surface (i.e., after loss of surface-lock, obtain the leading edge of the target echo as fast as possible again within the range window) and then track the surface (i.e., keep the target echo within the window). Overall, there are two acquisition and three tracking modes. Autonomous acquisition (as used by Jason-1) estimates the range from the nominal satellite altitude and the echo is searched for within a 50 km range window. In this mode, the expected rate of re-acquisition of the surface is better than ~4 s (~25 km, Lambin 2008). The new DIODE acquisition mode derives an estimated range (with respect to a geoid) from the DIODE altitude and searches for the echo in an adjustable 5 km range window. Reacquisition times are expected to be up to three times better (<1.3 s) than the autonomous mode.

The first of the tracking modes is the split-gate tracking (SGT) algorithm (used for Jason-1) that balances the received energy in the range window between three subwindows so that a typical ocean echo (Brown 1977) is centered. This serves ocean, inland seas, and large lakes well, but the limitation is poor tracking over calm, smooth surfaces where the reflection tends toward specular and the echo width is narrow. Such echoes are found over small or sheltered lakes, as well as over rivers and wetlands. The second tracking mode, the median algorithm, is expected to enhance tracking capability over the nonocean surfaces and is similar to that onboard ENVISAT and T/P tracking. In this mode the aim is to center the median power of any shape echo within the range window. The centering proves to have less stability than SGT mode, but tests have shown that additional postprocessing of the data can correct for any such instability with no loss of accuracy (Lambin 2008).

While these two tracking modes must be coupled with either of the acquisition modes, the third tracking mode, DIODE/DEM, is an "open-loop" option not requiring an acquisition phase. While the returned echo is assessed for power/energy considerations it is not evaluated for range. Instead, the position of the range window is estimated from the combination of DIODE altitude and an onboard Digital Elevation Model (DEM) which both use an EIGEN-GL04C solution geoid (Foerste et al. 2008) as the reference datum. The DEM is a 1 km horizontal, 1 m vertical resolution look-up file and is used in conjunction with the Generic Mapping Tools (GMT) mask that defines surface type. The DEM is based on the Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) HYDROWEB altimetric height database (~70 lakes, ~170 rivers, Crétaux et al. 2009) and also utilizes land elevations from the ESA ACE-1 digital elevation model (Berry et al. 2002). To comply with hardware limitations, only ACE land elevations within defined polygons (excluding mountainous terrain) are included. When the DIODE/DEM mode is selected the instrument interpolates the DEM elevation and the DIODE satellite altitude (both with respect to the geoid) to estimate the range in the along-track direction, and does so at the same rate

(2060-Hz) as the other modes. There may be regions around the world where the DEM lacks data or is erroneous. Because switching between modes and updating the DEM relies on uplink commands this may lead to a lack of height data in these regions when this mode is selected. Nevertheless this mode is expected to improve echo retention and analyses over inland water and coastal regions, though use of the DIODE altitude and the DEM are experimental and the final choice will depend on global assessment studies.

The Data Set

The raw altimeter data from Poseidon-3 are processed and placed in summary form into Level-2 Operational, Interim, and final Geophysical Data Records (OGDR, IGDR, and GDR). The OGDR are created by NOAA/EUMETSAT, and the IGDR/GDR are formed by CNES. There is a trade-off between data delivery time and expected (ocean) measurement accuracy ranging from ∼10 cm and 3 hrs (OGDR) to ∼1 cm and 2 months (GDR). Level 1 expert sensor products S-IGDR and S-GDR, containing the full radar echo waveforms, are also available. The study presented here utilizes the Jason-2/OSTM IGDR data. These records are available ∼1–3 days after satellite overpass and are the precursor to the GDR. Although the altimetric, orbital, and geophysical GDR parameters are more accurate, the GRLM program utilizes the IGDR to form its operational lakes products and so these interim records are the focus here. IGDR data were obtained from the Archiving, Validation, and Interpretation of Satellite Data in Oceanography (AVISO) ftp server for the first partial cycle (cycle 000, passes 055 to 254, July 4–12, 2008) and the full 001 through 051 cycles (July 12, 2008, to November 29, 2009). This includes version-T (Test) data (cycles 000 to 014) from the early verification phase and version-C data (cycle 015 onwards). The version-C data aims to match the data quality and standards of the Jason-1 version-C GDR and has three additional parameters in its data structure including a 20-Hz flag to denote the tracking mode type and a 20-Hz flag to denote the quality of the range measurements from the ice-retracker algorithm.

Cycle 000 contains test data in the various combinations of acquisition and tracking modes; autonomous acquisition/median tracking, DIODE acquisition/median tracking, DIODE acquisition/SGT tracking, and finally DIODE/DEM tracking mode. Cycles 003, 005, 007, and 034 (northern hemisphere summers) also tested the DIODE/DEM tracking mode noting that cycle 034 was performed with an upgraded DEM, which included Jason-2 median tracking mode data. A correction was also made to the altimeter tracking threshold parameters during cycle 016 (Dec 10, 2008) to rectify median tracker problems over regions of low echo power. Data over NE Siberia, for example, were originally poor with loss of tracking and long acquisition times. The fine-tuning reduced the altimeter's sensitivity to high sigma0 and avoided cases were the tracking was following an echo replica or "ghost" (J.-D. Desjonqueres, personal communication, 2009). All cycles other than those highlighted have been performed to date with DIODE acquisition/median tracker, the designated default combination.

The IGDR contain satellite altitude and altimetric range values at a rate of 20-Hz and geophysical corrections at a rate of 1-Hz, enabling the estimation of one average height value every 0.05 s or ∼290 m on the surface. This sampling is comparable to Jason-1 and ERS (both 20-Hz) and ENVISAT (18-Hz) and is an advantage over the 10-Hz GDR sampling of T/P, as this should, in theory, enable the better detection of smaller (100–300 km^2) lakes. Over uniform roughened ocean surfaces the altimeter echo has a well-defined shape known as ocean-like or Brown-like (Brown 1977) and various waveform-fitting techniques (Hayne 1980; Amarouche et al. 2004) enable key surface parameters to be extracted. Such fitting techniques are part of the data postprocessing (also known as "retracking") and continue to be refined and tested for both ocean and nonocean surfaces (Berry et al. 1997; Berry et al. 2005; Legresy et al. 2005; Frappart et al. 2006, Calmant et al. 2008; Lee et al. 2009; Enjolras and Rodriguez 2009). In the IGDR two range values are provided. The first is provided by the Maximum Likelihood Estimator (MLE-4, Amarouche et al. 2004, and also used for Jason-1 Version C data) and based on a 2nd order Brown analytical model. This "ocean-retracker" algorithm aims to locate the midpower point on the leading edge of an ocean-like waveform, a point that corresponds to the mean water level of a symmetric (Gaussian) distribution of surface waves. The ocean-retracker derives four variables; range, significant wave height, radar backscatter coefficient σ° (the ratio of reflected surface power to the incident power), and an estimate of the antenna mispointing angle (deviations from the nadir). The second IGDR range parameter is a product stemming from an algorithm designed to gain an elevation value over highly reflective surfaces. This algorithm is similar to the offset centre of gravity "ice-1" algorithm utilized with the ENVISAT data set for continental ice-sheet monitoring (Resti et al. 1999). The Jason-2/OSTM "ice-retracker" involves a geometrical analysis of the waveform and provides both range and σ° so long as there is some energy recorded in the waveform. In this respect a greater quantity of range values can be expected in comparison to the ocean-retracker output. The ocean-retracker then is suited to waveforms returned over large lakes and inland seas, that is, large bodies of open water with sufficient fetch to form significant wave heights (SWH). The ice-retracker range will be more applicable to the nonocean-like waveforms associated with the calmer, smoother waters (approximately <1.25 m SWH, degrees 0 to 3 or 0 to 4 on the Douglas/Beaufort Sea Scales) of small or sheltered lakes, as well as river channels and floodplains (see Birkett 1995 for echo types over inland water).

Note here that the IGDR are not a fully validated product and contain some preliminary corrections. At this stage of data processing the satellite orbits are provided only by the DORIS and SLR systems. The pole tide corrections are at the predicted, not restituted level, and the radiometer and dual-frequency ionospheric path delays are preliminary, not precise. However, the meteorological fields provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), that is, the dry tropospheric and wet tropospheric (alternative to the radiometer value) corrections and the Global Ionospheric Map (GIM, and the alternative to the dual-frequency derived ionospheric correction) should be at the same restituted level for both IGDR and GDR (see altimetric accuracy section for correction descriptions).

Methodology and Case Study Regions

Derivation of the variations in altimetric surface height with time take advantage of the repeat track nature of the orbit, which helps reduce uncertainties in the time invariant, geographically correlated components of the altitude error. Here, two methods are employed. The first as outlined in Birkett (1995) allows one repeat pass over the lake at a given date and time to be a "reference pass" and height differences between the reference pass and successive repeat passes are determined. Using the available full data rate (10, 18, or 20-Hz), no interpolation is deemed necessary to form consistent latitude/longitude points between repeat tracks prior to estimating these differences, instead a "nearest-neighbor" approach is employed. Birkett (1995) explored the along-track and cross-track slope error contribution to the range involved in this method and estimated a maximum of $\sim$2 cm in extreme cases (e.g., Lake Tanganyika). This error is acceptable considering the overall rms requirements of the USDA/GRLM program and the longer-term projects examining climate effects on the lake basins (10 cm rms for the largest lakes and inland seas, 20% of the expected seasonal amplitude for the smaller lakes). The second method (Birkett et al. 2009) follows similar techniques used in oceanography. Here, a reference pass is constructed by averaging all height profiles from the same satellite pass over a given time period to form an average profile. In this way, time varying wind, tide, and seasonal effects should cancel. For T/P, Jason-1, and Jason-2/OSTM analysis, the mean profile is based on an average of all valid T/P lake heights over a nine-year period. The result is a 10-Hz time-tagged reference datum with consistent latitude/longitude points formed via interpolation of the along-track T/P heights. For Jason-2/OSTM, height differences between this reference and a Jason-2/OSTM overpass are based on matching data points via a nearest-neighbor approach as its searches for the closest 20-Hz data point along the Jason-2/OSTM ground track. For either method, data filtering includes the rejection of erroneous data due to island or coastline interference or poor surface tracking. This is done via knowledge of the lake and ground track locations, the expected range of height variations, and the search for a uniform homogeneous surface of minimum height variability in the long-track direction. The output of both methods is a time series of relative height variations for a given lake and satellite pass.

This study concentrates on a global selection of lakes (Figure 1) with a range of surface roughness, size, and seasonality, and situated within differing terrains. They form a set of open and closed (no or minimal outflow) lakes and reservoirs, with those in the United States and Canada utilized for absolute validation exercises where ground-based gauge data are readily accessible. Table 1 provides lake and satellite pass detail for each lake.

Altimetric Accuracy

Birkett (1995) provided a full explanation of the construction of altimetric lake height and the expected accuracy over the lakes and reservoirs based on the T/P GDR. The problems associated with wind set-up effects, heavy rain, the presence of ice, and the effects of overlying vegetation and canopy were also discussed and similarly apply here. To summarize for Jason2/OSTM (see Dumont et al. 2009 for full details), the corrected

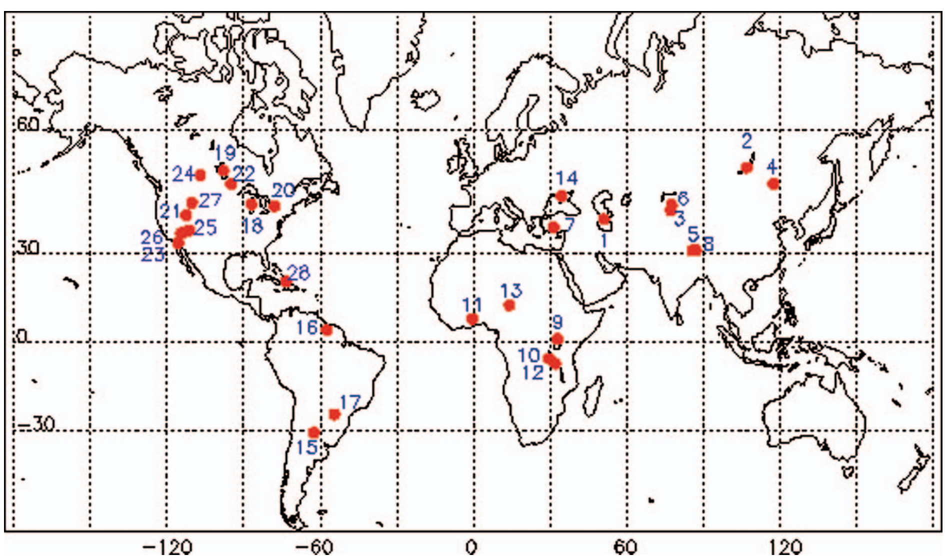

Figure 1. Distribution of the case study lakes and reservoirs (see Table 1).

Table 1
Test case lakes and reservoirs

Name	Country	latitude	longitude	Lake Area (km^2)	Satellite Pass* No.	Pass	Extent (km)
			Asia				
1 Caspian	Kazakhstan	40° 00′	51° 00′	380,000	9	092	1085
2 Baikal	Russia	52° 40′	107° 00′	31,500	6	062	60
3 Issyk-kul	Kyrgyzstan	42° 25′	77° 20′	6000	2	131	70
4 Hulun	China	49° 00′	117° 30′	2400	2	036	30
5 Chajih	China	30° 55′	85° 40′	900	1	090	10
6 Kapchagay	Kazakhstan	43° 50′	77° 30′	800	1	090	15
7 Beysehir	Turkey	37° 47′	31° 33′	550	1	007	25
8 Angtzu	China	31° 02′	87° 10′	300	1	079	20
			Africa				
9 Victoria	Tanzania	1° 00′	33° 00′	68,800	2	120	200
10 Tanganyika	Zaire	−6° 00′	29° 35′	34,000	2	222	450
11 Volta	Ghana	8° 10′	−0° 25′	10,000	2	046	35
12 Rukwa	Tanzania	−7° 50′	32° 00′	3,700	1	031	35
13 Chad	Chad	13° 00′	14° 10′	1600	2	248	10
			Europe				
14 Sivash	Ukraine	46° 00′	34° 30′	2,000	1	185	10
			South America				
15 Chiquita	Argentina	−30° 45′	−62° 35′	1,900	1	037	15
16 Brokopondo	Surinam	4° 10′	−57° 30′	1,500	1	063	10
17 Itaipu	Brazil	−25° 00′	−54° 27′	1,500	1	189	50
			North America				
18 Michigan	United States	44° 00′	−87° 00′	58,000	4	041	180
19 Winnipeg	Canada	52° 00′	−98° 00′	24,500	4	195	85
20 Ontario	United States	43° 35′	−78° 00′	19,000	3	015	70
21 Great Salt	United States	41° 10′	−112° 30′	4,400	1	119	5
22 Woods	United States	49° 05′	−95° 00′	1,900	2	178	45
23 Salton Sea	United States	33° 15′	−115° 45′	800	1	195	25
24 Diefenbaker	Canada	51° 00′	−107° 00′	550	1	043	<10
25 Powell	United States	37° 00′	−111° 28′	500	2	002	<1
26 Mead	United States	36° 10′	−114° 24′	500	1	195	<1
27 Yellowstone	United States	44° 25′	−110° 20′	350	1	154	15
28 Windsor	Bahamas	21° 02′	−73° 31′	150	1	217	15

Lake areas are approximations. *Number of Jason-2/OSTM satellite passes across the lake, the particular pass chosen for research and the approximate extent of water along this ground track.

altimetric range R_{corr} and the surface height H, with respect to the reference ellipsoid are given by

$$R_{corr} = R + A_{wet} + A_{dry} + A_{iono} + SSB \tag{1}$$

$$H = (Alt - R_{corr}) + T_{La} + T_E + T_P + T_L \tag{2}$$

R is the altimetric range that has been corrected for calibration and instrument effects such as the center of gravity motion and the calibration and pointing angle errors. The Doppler Shift and ultra-stable oscillator (USO) drift, related to the altimeter acceleration, are also included here. A_{wet}, A_{dry} and A_{iono} are the atmospheric corrections related to the water vapor and dry gases in the troposphere, and the free electron content in the ionosphere. SSB is the sea state bias, a combination of three effects: (i) an instrument-related tracker bias, (ii) the electromagnetic or embias, which relates to differences in radar echo contribution between the crests and troughs of surface waves, and (iii) skewness, which is associated with deviations from the assumption that the probability density function of heights within the instrument footprint is symmetric.

In Eq. (2), Alt is the satellite altitude, and T_{La}, T_E, and T_L are the lake, earth, and loading tides associated with the lunar-solar forcing of the earth. T_P is the pole tide associated with variations in the Earth's rotation. For lake studies, an inverse barometric correction associated with the response of the water surface to atmospheric pressure, is not applied in Eq. (2). This is in consideration of the fact that by comparison with atmospheric pressure systems, the majority of lakes are small closed systems. A correction for geoid undulation (the EGM96 model within the IGDR; Lemoine et al. 1998) is also not applied in Eq. (2) as the focus here is on relative variations with time.

For those large lakes and inland seas with wind-roughened unfrozen surfaces, a case can be made for the application of the radiometer-derived A_{wet}, the altimeter-derived dual-frequency A_{iono} and the model-derived SSB, all three parameters being applicable to ocean surfaces. Coastline interference and deviations of echo shape and power for the smaller or more sheltered lakes though forces the use of the alternate model-derived A_{wet} (ECMWF), A_{iono} (GIM), and assigns SSB = 0. The lake tide T_{La} is not provided within the Jason-2/OSTM IGDR. Birkett (1995) commented that spring tides can attain ~8 cm for large lakes such as Lake Superior and in general can be assumed to be ~1–2 cm. However, without auxiliary data for each lake this term cannot be corrected for. The IGDR values for pole tide are based on the equilibrium pole tide, which has been modified by Love numbers for ocean (scaling factor (1+k2) where k2 = 0.302) and land (scaling factor h2 = 0.609) applications. Inspection of the IGDR though shows that the pole tide correction for lakes has been incorrectly set to "ocean," and so a scaling factor of 0.468 (i.e., h2/1+k2) needs to be applied (R. Scharroo, personal communication, 2009). The Birkett (1995) repeat track method is flexible and partly manual. The various A_{wet} and A_{iono} options and the use of SSB are selected depending on the size of the target, the ground track/coastline separation distance, the magnitude and variability of σ° and knowledge of winter ice conditions, and the validity of the correction (not set to default values). The Birkett et al. (2009) method for the GRLM Jason-2/OSTM products is more automated. It currently utilizes the AMR radiometer wet correction if valid (i.e., not set to the default value and <0) and defaults to the ECMW if not. It also applies the GIM ionospheric correction and the same scaling factor to the pole tide and sets the SSB correction to zero. In both methods the lake elevations utilize the IGDR solution-1 load tide option and employ an identical range retracker (ocean or ice) for a given target. Note that the Birkett et al. (2009) method currently outputs version 1 (preliminary) Jason-2/OSTM products, and both techniques will undergo review when all performance assessment studies are completed.

Dumont et al. (2009) provide an estimated error analysis on the 1-Hz (i.e., twenty 20-Hz measurements) altimetric and geophysical parameters and corrections for average ocean conditions (2 m significant wave height and 11 dB σ°). Assuming similar values for the largest of lakes (Table 2) we have an overall root sum square (RSS) corrected range (R_{corr}) error of 3–4.5 cm, depending on the range corrections chosen. Orbit altitude errors

Table 2
1-Hz IGDR lake height error budget

Contribution	Root-mean-square cm
Satellite orbit	2.5*
Range precision	(1.7)**
Wet trop. ECMWF/AMR	3/1.2
Dry troposphere	0.7
Ionosphere, GIM/DUAL	2.0/0.5
Earth+Pole+Loading tides	1
SSB	2
Minimum total	4.04/5.26

*The removal of geographically correlated orbit error components via the use of repeat track techniques may reduce this value.
**Variable with surface roughness and target size.

of 2.5 cm (IGDR) and combined tidal errors of ~1 cm place the RSS on an averaged 1-Hz lake height at ~4–5 cm. Preliminary results from the Seattle 2009 Jason-2/OSTM Science Working Team (SWT) meeting have confirmed some of the error contributions. For example, the ocean-retracker range precision over the oceans is estimated at ~1.6 cm, the IGDR altitude error is <2.5 cm, and the error on A_{wet} is in the range of 0.1–0.8 cm (G. Zaouche, personal communication, 2009). We can take the values in Table 2 then as first estimates noting the global altitude error is not thought to be highly geographically variable and its relative (repeat track) accuracy can be significantly better due to the removal of the time invariant, geographically correlated components.

The 1.7 cm estimate for R is the range precision, a measure of the internal consistency or repeatability of the instrument. It is dominated by the error associated with estimating the location in the range window of a predefined point on the leading edge of the returned echo (the retracking point is in range window bin 44 for Poseidon-3/SGT mode). For an ideal ocean echo, this point corresponds to the mean surface height in the altimeter footprint and is derived by interpolating across adjacent range bins of a given resolution. The altimeter response to lakes is not always similar to oceans and will change according to surface conditions. The range precision will thus vary on a lake-by-lake basis, noting extreme cases of super-calm or "glassy" water (specular echo) where the majority of echo power will be located in a single range bin of ~0.5 m resolution. Complex, multipeaked echoes can also arise where islands, coastlines, and multiple small water targets are within the effective footprint making the association of a range value to a single identifiable target difficult both to achieve. In cases where the target can be easily identified, the range precision can be improved via averaging all available heights, from coast-to-coast, along the satellite ground track, effectively reducing the error by $1/\sqrt{N}$ where N = Number of valid measurements. This will not be the case for smaller targets where only a few 20-Hz height values are available, and in addition the overall height accuracy will be affected by the use of the model-derived A_{wet} and A_{iono}. The former depends in part on radionsonde measurements, and these can be sparse in many regions. For the latter, the GIM model may be in error by ~14% of the correction value, the error being strongly dependent on location, time of day, and solar activity (Scharroo and Smith 2010). While waiting for additional Jason-2/OSTM SWT feedback on the accuracy of the model-based parameters, we will assume here a 3 cm (based on the historical T/P error budget; Birkett 1995) and 2 cm global average for the model-derived A_{wet} and A_{iono}, respectively.

Heavy rain events and the presence of lake ice in the footprint can cause a bias in the range measurement, and where possible such data must be identified and either highlighted or rejected. Based on local and global calibration/validation ocean experiments, it has been found that the Poseidon-2 and Poseidon-3 altimeters are measuring too high with range biases of $\sim$10 cm and $\sim$17.5 cm, respectively, and research communities continue to revise these estimates (Willis 2009). Although this is not a concern for a time series of Jason-2/OSTM relative height variations, the merger of Jason-2/OSTM results with those from Jason-1 for the USDA/GRLM lake products or otherwise will need to apply an inter-mission bias of $\sim$8 cm to the Jason-2/OSTM measurements.

Investigations

IGDR Parameter and Flag Assessment

The IGDR data contain a mix of 1- and 20-Hz altimetric and geophysical correction parameters, as well as instrument status and data quality flags that need to be explored to assess their usefulness when observing the full range of lakes and their varying surface roughness and seasonal effects. The status of the instrument and the current tracking mode also need to be noted. Inspection of the flags indicating rain events, the current altimeter tracking mode, and the success of the interpolation of the microwave brightness temperature (for the radiometer-based wet tropospheric range correction) were found to be redundant and set to their default values in the version-C data. The acquisition mode flag correctly depicts periods of DIODE acquisition sequences but is set to zero (meaning autonomous acquisition) instead of its default value for blocks of IGDR records where the time, latitude, longitude and range parameters are set to their default values.

Investigation of the mask-based and radiometer-based surface-type flags shows that their resolution (1-Hz) and dependency on the instrument-based wet tropospheric correction excludes them from studies of the smaller-scale inland water bodies. The former cannot always correctly distinguish lake water from coastline and remains set to "land" long after an island has passed out of the footprint. The latter fails to indicate water over calm-water regions. Lake Chad, for example, is set to "land" across its basin. The "presence of ice" flag, which is based on the number of valid ranges within a 1-Hz set plus the output from both the wet tropospheric range correction parameters, is not applicable over waters with low SWH. While it cannot identify ice during the winter periods of Lake of the Woods and Yellowstone Lake, it is correctly set to "ice" during the late spring (April/May) periods over Lake Baikal.

The three radiometer brightness temperature quality flags are being set correctly over the majority of large lakes indicating "good" when the radiometer wet tropospheric correction is within the expected range of values and "bad" as the instrument approaches the coastline. However, these quality flags have been found set to "bad" when the radiometer correction has a comparable value to its model-based counterpart (ECMWF) and is within its expected range of values. They can also be set to "good" over frozen lakes with in-range wet correction values when the radiometer technique is in fact invalid over ice covered surfaces.

A number of flags relating to the quality of the ocean-retracker range were also explored but found to be limited due their 1-Hz resolution and echo assumptions. These include the range and instrumental range correction flags which can both be set to invalid near the coastlines of large lakes but where the ocean-retracker elevations are within expectation. When there is no ocean-retracker output the range quality flag is correctly set to invalid (e.g., Lake Chad). In these cases an equivalent ice-retracker range flag would be helpful, and one is available, but its use is limited appearing to be only set to “invalid” for those IGDR blocks of defaulted latitude/longitude/range records. The IGDR data set does though attempt to verify the validity of the individual 20-Hz waveforms during the process of forming a 1-Hz mean elevation. Inspection of the data over Lakes Ontario (ocean-like waveforms) and Chad (peaky waveforms) though reveals great variability in the number of “valid” waveforms and additional research is required with the aid of the S-IGDR (waveform) data set.

Focusing on some of the range correction parameters and surface characteristic flags, the IGDR offers two parameters relating to loading tide. Both have similar magnitudes, with the majority set to 0 or 1 cm. The pole tide correction is also small, often in the range of 0–2 cm. The sea state bias correction is mostly defaulted over the smaller or more complex lake basins such as Lake Chad, but valid values are found over the larger open lakes. Over Lake Victoria, for example, sea state bias values are found to be in the range of 0–3 cm, notably rising to 8 cm at the lake edges. Over Lake Ontario, values typically ranged from 1–10 cm but increased at the coastline and during calm periods. Interestingly, observation of the 20-Hz radar backscatter coefficient σ° for Lake Ontario can be highly variable throughout both the summer and winter seasons reflecting both calm and icy conditions. The σ° associated with the ice- and the ocean-retrackers shows that the former is smaller in magnitude than the latter by ∼1 dB during wind-roughened periods ($10<\sigma^\circ<15$ dB). When calm or icy conditions prevail, both values becomes highly variable across the lake (Figure 2).

The IGDR also offer three waveform characteristic parameters that could be used to identify calm or icy waters. The echo-type parameter identifies waveforms that are not ocean-like, though as a 1-Hz flag summarizing a set of 20 echoes it has its limitations near the coastlines. The echo-peakiness parameter is based on an algorithm that examines the ratio of maximum waveform amplitude to the mean amplitude of the waveform samples to the right (higher range end) of the range tracking point (Dumont 2009). Peakiness values over Lake Ontario are generally ∼2.5 but increase with increasing σ°. Over more sheltered targets, values are >3.5 (e.g., Lake Chad, Lake Powell with maximum σ° ∼55 dB). Synergistic high values of peakiness and σ° can also be found over frozen lakes though as noted earlier, the “ice-flag present” flag is not always valid. The 20-Hz mean quadratic error (MQE) parameter indicates differences between the actual waveform samples and a model-based form built from the ocean-retracker output. It essentially provides an error on the fit to an expected ocean-like waveform. The flag is not set when the ocean-retracker range is set to default but otherwise typical MQE values over Lake Ontario are ≤0.1 increasing at the coastline (land interference) and during periods of calm or icy waters. Similarly to the waveform validity flag, the peakiness and MQE parameters require further investigation within the scopes of an IGDR/S-IGDR study.

To summarize, several of the IGDR flags and parameters appear not to be set, and the majority of the data quality flags are limited for inland water use due to their availability at 1-Hz and inherent assumptions of surface roughness based on typical ocean response. For the largest of lakes and inland seas, data users could utilize the quality and land mask flags and accept some loss of height information without compromising accuracy. But for lake and reservoir studies as a whole, users must adopt a more manual approach. The use of maps and satellite imagery is required to determine the coastline crossing locations. The IGDR parameters utilized in the construction of surface elevation should be checked to ensure that they are in their expected validity range. For example, one can ignore

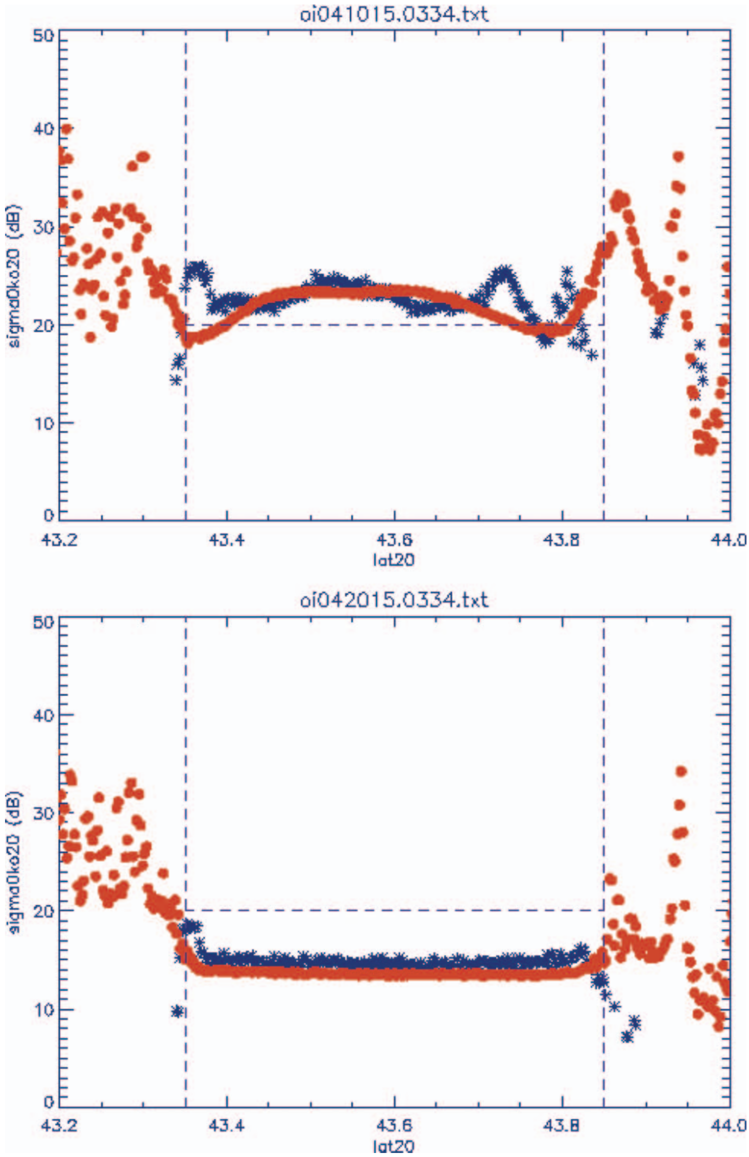

Figure 2. Difference between the radar backscatter coefficients associated with the ocean-retracker (blue) and the ice-retracker (red) for Lake Ontario pass 015. Top figure refers to calm water conditions on August 13, 2009, cycle 041; the bottom figure is for rougher ocean-like waters observed on August 23, 2009, cycle 042.

the radiometer quality flags but still check the range of expected wet tropospheric range correction from the data manuals (Dumont et al. 2008; Dumont et al. 2009). A priori knowledge of the lake's elevation and seasonal variation, as well as freeze/thaw periods, can also aid analysis. In this respect, observation of the altimetric heights and associated σ°, waveform peakiness, and MQE parameters can enable data rejection or highlight potentially erroneous winter elevations. Note that in both the repeat track methods utilized here (Birkett 1995; Birkett et al. 2009) the number of valid waveforms or elevation points, N, and the along-track height rms are utilized as a form of data filtering. In the Birkett (1995) methodology, both N and the rms can be varied depending on target size and surface roughness. Jason-2/OSTM IGDR users should also be aware of the blocks of defaulted latitude/longitude/range values and to note the current instrument tracking mode by the separately issued mission events table.

Wet Tropospheric and Ionospheric Range Corrections

The wet tropospheric range correction is highly spatially and temporally variable and can attain maximum values of ∼35–50 cm in tropical atmospheres. The advantage of the AMR over the ECMWF model-derived correction is clear considering coincident measurements with the radar altimeter. The limitations, though, are that the AMR measurements are not deemed valid within ∼15–20 km of land due to the radiometer footprint, and it is not a valid technique over frozen water. Thus the application of the AMR correction is restricted to the central regions of very large lakes and inland seas. The uncertainty in the ECMWF correction (3 cm rms) is dependent in part on the distribution and frequency of ground observations, and these can be sparse in many regions.

With the version-C IGDR (cycles 015–051, ∼1 year), a study of the AMR and ECMWF values across the different continents shows there can be excellent agreement between the two (e.g., to ∼5% for Lakes Victoria (Figure 3), Tanganyika, Beysehir and the Caspian Sea) and in general they display the same seasonality. For many other lakes though, the ECMWF shows a higher humidity level (i.e., a greater negative range correction value) than the AMR by amounts ranging from ∼10% (Lake Ontario) to ∼30% (Lake Chiquita, Figure 3). Although not considered valid over ice, it is interesting to note that the IGDR does contain in-range AMR corrections over lakes that freeze (e.g., Lakes Winnipeg, Baikal, Lake of the Woods). For these targets, the ECMWF displays lower humidity than AMR during the winter period (notably November to March) but averaged over the one year the ECMWF still has the greater humidity. This bias between ECMWF and radiometer has been noted in the past by Stum (1994) who found that the ECMWF model was biased higher in regions of high humidity, a point also noted by Birkett (1995) during analysis of the T/P GDR data set. Data users though have the option of either correction with noted limitations on the AMR near the coastline and over ice. Unlike some of the T/P GDR data the ECMWF correction does appear to be present in the Jason-2/OSTM IGDR data stream for most study regions here.

Observation of the 1-Hz dual-frequency ionospheric correction shows that IGDR values are mostly defaulted over small bodies of water. Over the center of larger lakes the mean value is found to be mostly comparable (to within 1 cm) to those from the GIM model but there are exceptions, notably near the coastline when the instrument value can be significantly higher due to land contamination effects. Seasonal variations of both corrections over large unfrozen lakes also reveal the much higher variability of the dual-frequency based correction (Figure 4).

The instrument-based AMR and dual-frequency ionospheric corrections (as well as the ss bias correction) can be utilized over the center of large unfrozen lakes and inland seas. However, because the dual-frequency correction was found to be less accurate during validation exercises and because its high variability could be problematic, the methods employed here for all the lake sizes ultimately rely on the GIM-based model which is unvarying over spatial scales of ∼170 km. For the smaller water bodies a similar check is made on the AMR parameter for expected range validity, clearance distance between water

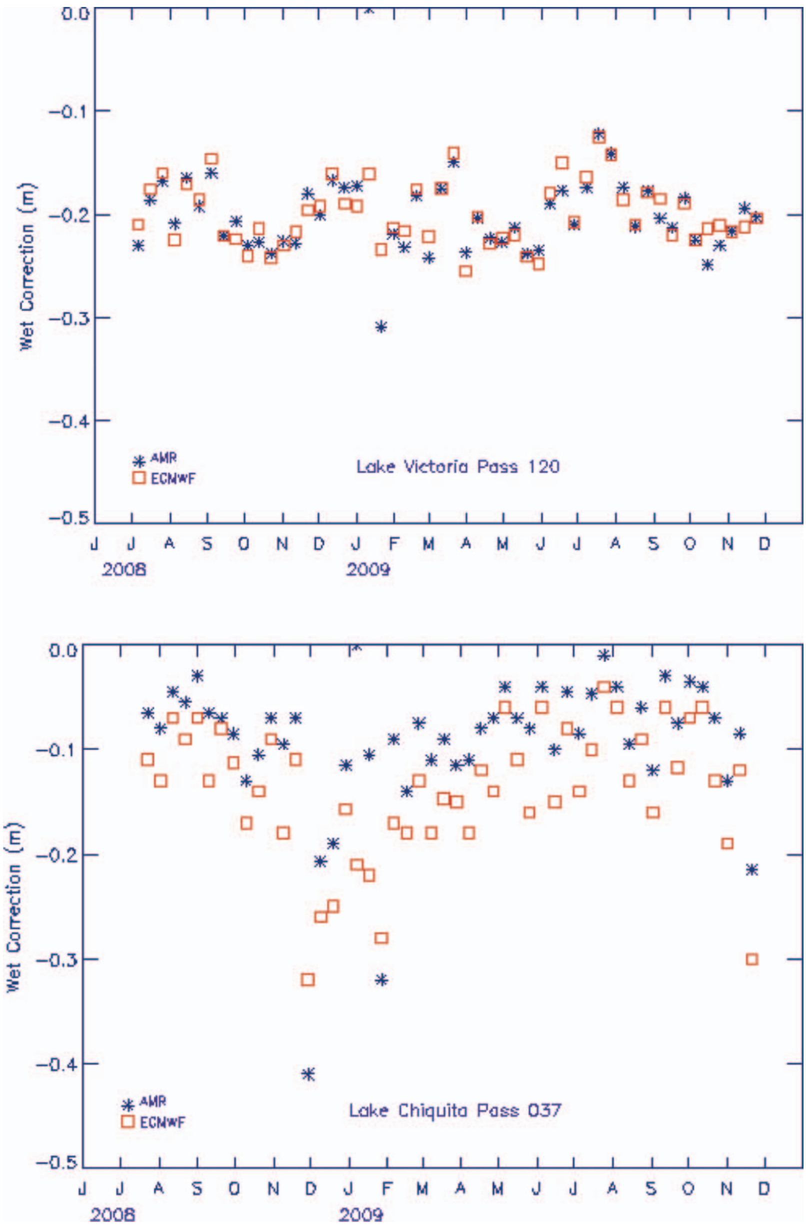

Figure 3. Differences between the AMR and ECMWF wet tropospheric range correction for Lake Victoria (top) and Lake Chiquita (bottom).

and coastline and the presence of ice, defaulting to the ECMWF correction for all cycles if needed.

Altimetric Range

The IGDR contains two range values: the output from the ocean-retrackers and from the ice-retrackers. Both values can be available, but in many small-lake cases only the

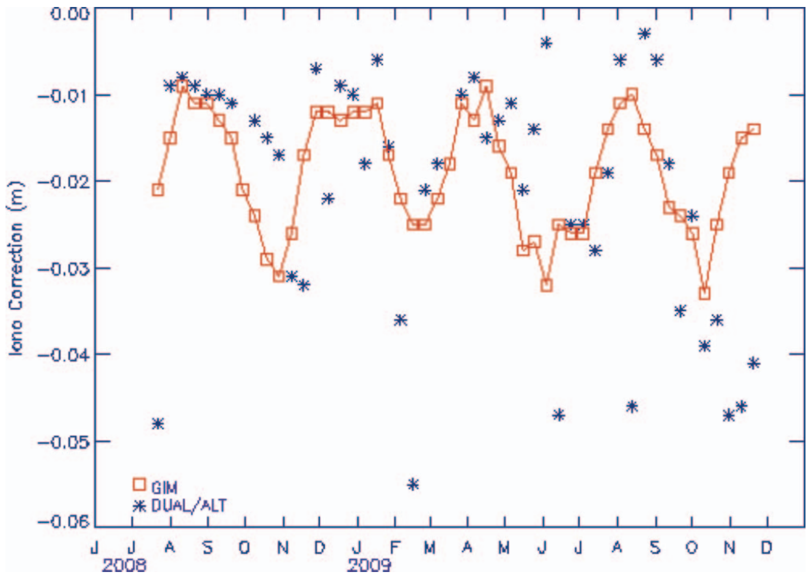

Figure 4. Differences between the dual-frequency and GIM model ionospheric range correction for Lake Ontario pass 015 cycles 000 to 051.

ice-retracker range is present. Observation of the associated height values shows that the majority of ice-retracker heights are biased higher (range biased lower) than those derived from the ocean-retracker (Figure 5a). This bias could be due in part to the different approaches in analyzing the radar echo, the two retracked locations within the waveform translating to range measurements associated with different physical quantities (e.g., mean versus nonmean height for ocean-like waveforms). The observed IGDR range bias is variable, both across the lake and with time. Averaging along track, and over the 51-cycle time span for those lakes where both retracker ranges are available, and rejecting island and coastline regions, reveals mean bias values between 17 cm (Lake Baikal) and 29 cm (Lake Ontario). The bias also increases with decreasing σ° in the 10–16 dB range (Figure 5b) though this is less pronounced for the waters of the African lakes, Victoria and Tanganyika, where σ° values rarely drop below 14 dB. Dumont et al. (2009) state that the ice-retracked range corrections include center of gravity, USO and internal range corrections, but Doppler, modeled and system bias corrections (included in the ocean-retracker range) are not highlighted. This may be a contributing factor, but the ~20 cm range bias, approximately half the width of a range window bin, is more likely due to differences in retracker assumptions/methods and requires further investigation. Data users though should not mix the differing ocean/ice-retracker output over a given satellite pass. If both exist, the ocean-retracker range should be prioritized for lake surfaces exhibiting ocean-like waveform characteristics (see validation section).

Estimates of the range precision can be obtained by observing the along-track scatter (rms about a mean) on the height measurements. To avoid geoid undulation effects (gravity-related variations), short along-track distances are chosen. The IGDR provides a 1-Hz along-track rms value (averaged over 5.8 km) based on the filtered ocean-retracked ranges. A similar rms for the ice-retracker range was additionally computed based on the variations in the ice-retracked height, but no height filtering other than to geographically select lake

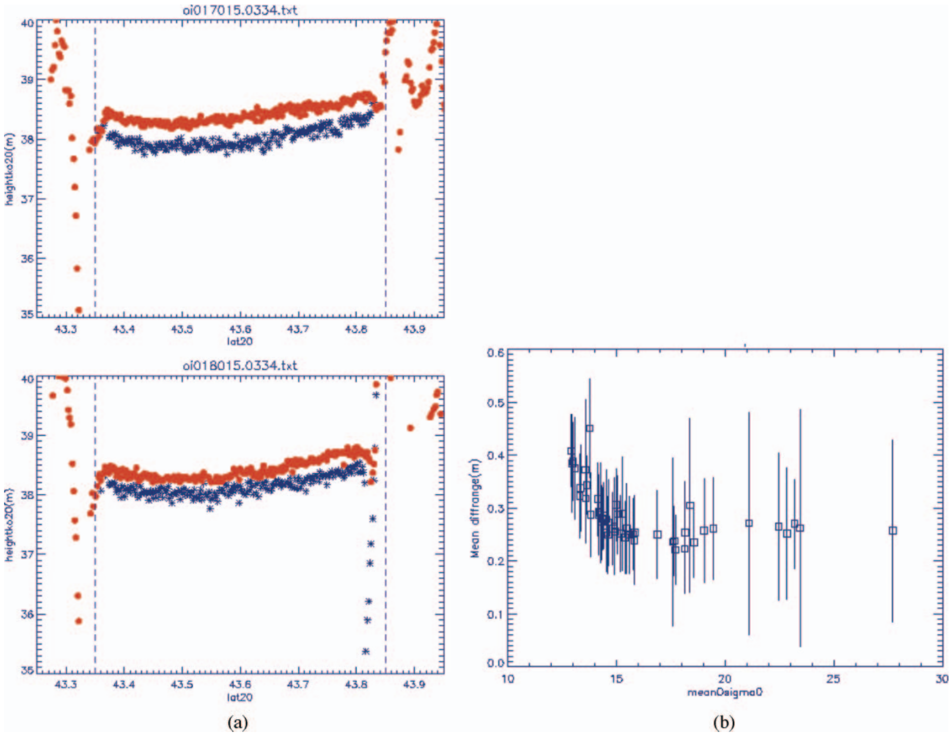

Figure 5. **(a)** Range bias between the ocean- (blue) and ice- (red) retrackers for Lake Ontario pass 015, for cycle 017 (top figure, December 18, 2008, mean = 12dB) and for cycle 018 (bottom figure, December 28, 2008, mean = 13.5dB). **(b)** Along-track mean range bias as a function of mean (ocean-retracker associated) radar backscatter coefficient, $\sigma°$, for Lake Ontario derived from IGDR cycles 000 to 051. Low $\sigma°$ values are associated with large significant wave height. High $\sigma°$ values are associated with periods of calm water or ice. The average range bias over all 51 cycles is 29cm. Error bars reflect standard deviation on the range bias.

water location is employed. The resulting rms values have some variation across each lake and between repeat cycles. The ocean-retracker rms values also show a greater variability associated with surface roughness. The smoother the surface, the narrower the waveform, the greater the ocean-retracker rms value as the logic interpolates a range value from a decreasing number of range bins. Examining the 1-Hz rms across Lake Ontario and Lake of the Woods, minimum values associated with the ocean-retracker heights were found to be 3 and 6 cm, respectively. Minimum ice-retracker rms varied from 1 cm (Lake Ontario) to 4 cm (Lake of the Woods) to 12 cm (Lake Chad). As an approximation to range precision, these values clearly deviate from the estimated 1.7 cm in Table 2 for a 1-Hz lake sample but can be improved upon by averaging across the lake surface.

There have been discussions on tracker range bias and compensations via retracking methods at the Jason-2/OSTM SWT meetings. One group of reports also discussed a "saw tooth" effect that was evident in the DIODE/DEM waveforms and the possibility of a cyclic bias in the range estimates that could vary in magnitude with a repeat period of 30 s (P. Thibaut, W. Smith, G. Quartly, personal communication, 2009). As this period translates to an along-track distance of 175 km, it may only affect the largest of lakes and inland seas and is merely noted for now pending further investigation).

Target Acquisition

Although the altimeters are designed for continuous operation, surface height data are not always available at each ground track location and for every repeat cycle. Data loss can be caused by ground station acquisition problems, ground data processing anomalies, and instrument anomalies. The altimeters also have to respond to varying degrees of terrain variability and surface conditions. Mountains and man made structures within the vicinity of the lake, the lake coastline itself, and periods of freeze/thaw conditions can also lead to loss of surface lock or erroneous elevation measurements. The speed of locating the surface and the ability to maintain the surface within the range window will depend on instrument characteristics and the on-board tracking logic. Ground reprocessing of the data (success of the various retracking routines) will also assist with surface identification and revise the altimeter range measurement. All of these factors together with the available IGDR data rate (20-Hz) will contribute to the number of surface measurements available across the lake and determine data losses in the coastline to water transition zones.

Early studies of the performance of the T/P NRA altimeter based on GDR observations showed that large lakes could be monitored down to a minimum size of ~300 km^2 and combined-factor (on-board acquisition/tracking, post-processing and a 10-Hz data rate) acquisition times varied between ~2.5 to 3.0 s (11.6–17.4 km from the coastline) in gently undulating terrain, to ~3–30 s in rugged terrain (Birkett 1995). Observation of the Jason-1 IGDR showed similar results but the extra on board data filtering hampered performance checks over targets <300 km^2 (Birkett et al. 2009). Preliminary investigations by the Jason-2/OSTM SWT suggested that Poseidon-3 DIODE acquisition speeds could be better than 0.5 s (Desjonqueres et al. 2010). For the lakes and reservoirs in Table 1 then, the Jason-2/OSTM IGDR data were explored to examine the quantity of data over each target and to determine the location of the first valid height measurement after the coastline crossing. In all cases, the lake surface is defined by a within-expected-range height value and a uniform along-track height rms. Again ‘acquisition time’ refers to IGDR data observation, that is, the combined results of on-board tracking and postprocessing retracking.

With respect to acquisition times, this varied with repeat cycle, target, tracking mode, and retracker ouput. For some large lakes (e.g., Lake Ontario, Lake Rukwa, Lake Hulun) the DIODE/DEM mode (cycles 003, 005, 007, 034) output with either retracker, consistently showed the same acquisition times, which were faster than the DIODE/median cycles. In these cases the DIODE/median acquisitions displayed greater variability. For others (e.g., Lake Victoria), the consistency did not hold across all four DIODE/DEM cycles, and for some bodies of water (e.g., Lake Issyk-kul) both the DIODE/median and DIODE/DEM tracking modes did equally well, neither having a clear advantage. Unless studying height variations at the coastline though, the benefit of either on-board tracking mode is marginal for such large lakes where plentiful data can be found over the central regions.

It is interesting to note the degree of success of the trackers/ice-retracker in difficult and high altitude terrains. For example, pass 063 descends from the mountains to skim across many of the narrow eastern sections of the Brokopondo reservoir in Surinam, just south of the dam location. At this location the ice-retracker output provides measurements for 80% of the post cycle016 repeat passes. Data are also available for all the Lake Issyk-kul repeat cycles (001 through 051), despite the surrounding mountains, and for all of the Lake Hulun cycles, although caution must be exercised with the winter Hulun observations due to problematic ice-penetration effects. Both the ice- and ocean-retracker ouput have almost 100% success rates in providing data for each repeat cycle for Lake Rukwa (Figure 6a), compared to the 25% success rate found from T/P GDR observations.

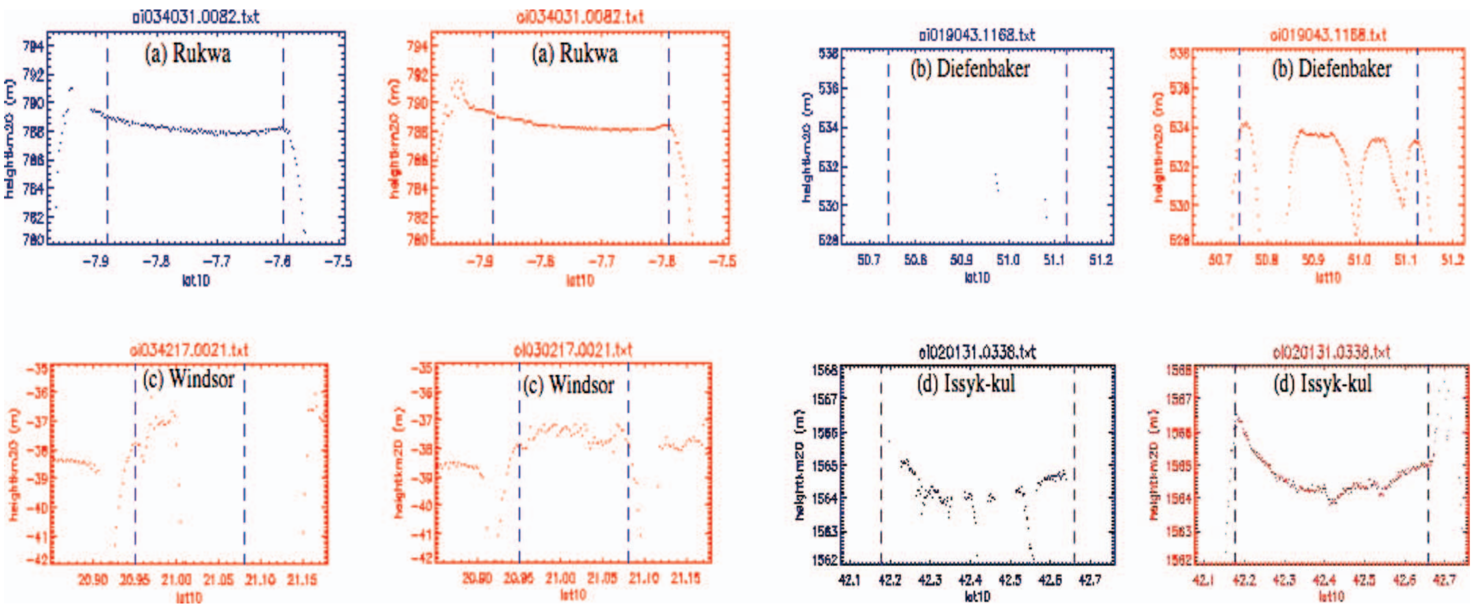

Figure 6. Surface water height profiles derived using the altimetric ranges from the ocean-retracker (blue) and ice-retracker (red) for **(a)** Lakes Rukwa, **(b)** Diefenbaker, **(c)** Windsor, and **(d)** Issyk-kul. For a given lake the profiles are for the same cycle and satellite pass except Windsor where cycle 034 (left) and cycle 030 (right) are shown to show DIODE/DEM mode loss over the lake. Dashed lines indicate either revised lake extents or the utilized lake extent based on earlier T/P investigations. Observations are May/June for Rukwa and Windsor, and December/January for Issyk-kul and Diefenbaker.

For Lakes Ontario and Victoria, observation of the first valid ocean-retracker height measurements after the satellite crosses the coastline varies from 0.65–2.85 s (3.8–16.5 km) with a mean of ∼1 s (5.8 km). The ice-retracker gains at least five more measurements near the coastlines in each cycle. This is observed in many of the case study lakes and is a result of the ice-retacker's echo interpretation methods. For Lake Rukwa, the ice-retracker acquisition times are in the range of 0.25–1.5 s, which can be compared to the 1–3 s observed via the T/P GDR measurements. Lake Hulun and Issyk-kul ice-retracker acquisitions are faster, 0.05–1.5 s, with means of ∼0.5 s and ∼0.25 s, respectively. For the Brokopondo reservoir and Lake Chajih, the majority of the acquisitions are within ∼0.1 s.

At the smaller end of the target size range the Powell and Diefenbaker reservoir systems pose an interesting challenge with narrow water extents and approach paths that cross steeply declining gradients. The Jason-2/OSTM satellite crosses over four sections of Lake Diefenbaker (Figure 7a) that range in width from ∼2.4–10.2 km. The ocean-tracker output offers few measurements prohibiting its use (left hand portion of Figure 6b). The ice-retracker however provides the required measurements noting that in this case the DIODE/median mode is outperforming DIODE/DEM, there is no valid height measurements recorded within cycles 003, 005, and 007, and valid data are only present for two lake sections within cycle 034. The DIODE/median tracker provides some measurements for all its associated cycles. As similarly observed for Lake Hulun (where acquisition speeds also improved post cycle 016), Lake Chajih, and the Brokopondo Reservoir, there is a considerable version-T to version-C improvement in quantity of measurements available. Within version-C, valid data are present ∼55% of the time for section 1 (nearest the approach path of the satellite, and the narrowest extent), 86% (section 2, the widest), 91% (section 3), and 97% (section 4). These statistics decline for version-T to 0%, 46%, 66%, and 73%. The version-C improvement could correspond to the fine-tuning of altimeter parameters performed on December 8, 2008 (within cyle016). For this lake there is little loss of data (<0.1 s) at the coastline though occasionally an acquisition time of ∼1 s can be observed for the widest section 2.

For Lake Powell, Jason-2/OSTM passes just to the south of two water storage areas before crossing two sections of the Colorado River (Figure 7b). These narrow extents, 800 m and 1,500 m along track, only offer ∼3 and ∼5 20-Hz elevation measurements. The measurements over the more northerly ∼800 m section though do correspond well to gauge data much further to the west at the Glen Canyon Dam (see validation section), and so are included here for comparison. The capability to acquire this section of the Lake Powell system does give an indication of the potential performance over large rivers in mountainous terrain. Based on the most northerly river crossing the version-T data only contain ice-retracker data within the DIODE/DEM cycles 003, 005, and 007 but these values were later rejected because they proved erroneous. Ice-retracker output is available though for DIODE/DEM cycle 034 and for ∼90% of the DIODE/median tracker cycles within the version-C cycles, with little loss of data (<0.1 s) at the land/water transition zone.

Lake Windsor on the island of Great Inagua in the Bahamas is also an interesting case study. The lake (∼150 km^2) covers a quarter of the island's interior and much of the remainder is swamp. The satellite ascends up over the ocean and across an ∼2 km strip of land/swamp before passing over the lake (Figure 7c). Little data are output by the ocean-retracker but the ice-retracker retrieves valid measurements for most cycles with only a delay of only ∼0.1 s in either DIODE/DEM or DIODE/median tracker mode (Figure 6c). However, after an along-track distance of ∼5 km all the DIODE/DEM cycles loose the lake surface and height measurements only reappear in the IGDR some distance later when the satellite is over the ocean. This could reveal inadequate resolution and/or data in the DEM.

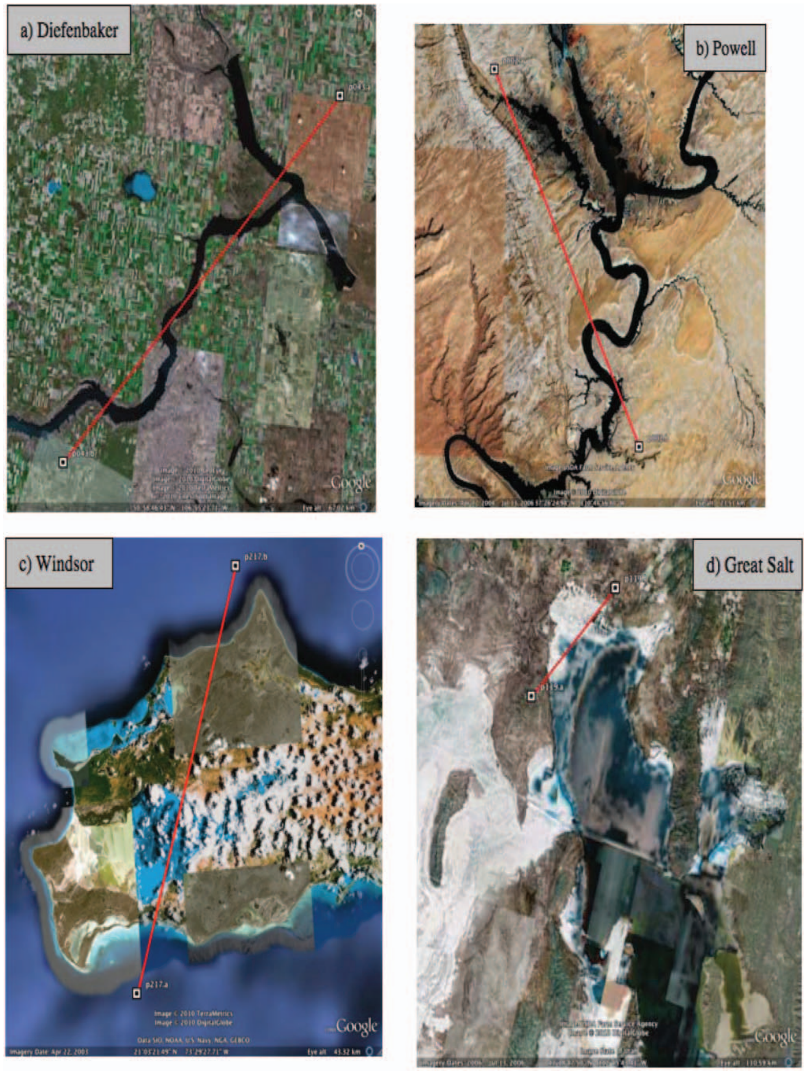

Figure 7. Satellite imagery depicting Jason-2/OSTM ground track locations (in red) across **(a)** Lake Diefenbaker, **(b)** the Powell reservoir region, **(c)** Lake Windsor, and **(d)** Great Salt Lake. Images are courtesy of the 2009 Google Earth software and Maps service.

The same smooth transition from swamp to permanent lake waters can also be seen in the ice-retracker output for Lake Chad, Africa where valid height measurements are gained across all the calm water regions successfully, regardless of on board tracking mode.

Moving from the marsh areas of the Sahel to the more drought-prone region of the Great Salt Lake in the United States, the DIODE/median tracker/ice-retracker combination is once again providing a substantial quantity of surface height information for both the surrounding salt flats as well as the narrow expanse of lake water (Figure 7d). In this case there appears to be a seamless transition from land to water. A most notable finding here is that there is no height information recorded within the DIODE/DEM cycles. Performance checks on other dry bed regions such as the Etosha Salt Pan (Namib desert) and Lake Eyre (Australia) show the same DIODE/median tracker/ice-retracker combination provides height measurements across much of these surface types, too. Although further investigation is needed, this bodes well for studies of ephemeral lakes both within the USDA/GRLM and the various science programs.

The cases of Lakes Powell, Chajih, Brokopondo, Windsor, and Diefenbaker show that in some regions the DEM may be in error or lacking data. Where DEM cycle 034 measurements exist, it is not clear whether this is due to the DEM upgrade or to the fine-tuning of altimetric parameters in cycle016. There are also additional cases where severe loss of IGDR data across both tracking and retracking modes has been observed. Lago Poopo situated in a shallow depression to the west of the Altiplano Mountains in Bolivia is one such case. Here, ice- or ocean-retracker data exists only for 5 cycles in the version-C data set. Many of the remaining cycles appear to be geographically truncated so that the lake area is excluded. The same situation holds for Lake Angtzu high up on the Tibetan Plateau. Again many cycles are truncated, either near the lake coastline or midway through the lake overpass. Such geographically truncated data could indicate data download problems.

As well as providing additional measurements near the coastlines, the ice-retracker proves to have several other advantages. For partly or wholly, calm or frozen (smooth) surface conditions, when σ° attains high and variable values (>16 dB), the majority of the ice-retracker heights contribute a smooth (low along-track height rms) profile across the lake. During these periods or at these locations across the lake, the ocean-retracker heights are less stable (examples include Lakes Victoria, Rukwa, Hulun, and Lake Issyk-kul in Figure 6d), and there is a reduced quantity of valid data. Examining pass120 over Lake Victoria it is also clear that the ice-retracker has better capability at maintaining the water surface as the satellite crosses over, and skims alongside, several small islands.

The Poseidon-3 altimeter and data set serve the user well. On board acquisition and tracking modes, additional ground retracking and a 20-Hz resolution, combine to not only more quickly acquire the targets that have been the focus of the T/P and Jason-1 related programs to date but also have the ability to gain targets within mountainous terrain and in the 100–300 km^2 size category. Comparing the performance of the on board tracking modes via the IGDR ocean- or ice-retracker output, there is no clear case for selecting the DIODE/DEM mode over the DIODE/median mode with the current form of the DEM. While DIODE/DEM mode can have the fastest acquisition times, it can also wholly or partially fail over some targets. No clear advantage could also be seen to the upgrade of the DEM in cycle 034. The DIODE/median tracker/ice-retracker combination, however, is able to acquire coastline waters and maintain lock with greater stability over calm or icy waters. For several targets this combination led to improved data quantity after the instrument parameter tuning during cycle 016. IGDR data also reveal that the same combination can result in lake elevations being acquired faster than 0.1 s or to within ~580 m of the coastline. Although this varies according to target (exceptions up to ~2.5 s) the majority of acquisitions are observed to be better than 0.4 s (~2.3 km) agreeing with the preliminary findings of the Jason-2/OSTM SWT. Results show that lakes and reservoirs at the 150 km^2 size, or an expanse of water ~800 m-wide can be acquired. These acquisition times and size limitations are an improvement for both the science-related and operational-based lake study programs. Many previously (T/P, Jason-1) unobservable lakes such as Brokopondo, Sivash, Itaipu, the Salton Sea, Kapchagayskoye, and Lake Mead can now be monitored. Because the USDA/GRLM operational program is focused on large lakes $\geq$100 km^2, we can now expect the majority of the smaller lakes to be observed by Jason-2/OSTM. The 800 m also gives an early indication of the width of river reach that can be similarly monitored.

Table 3
Altimeter validation

Lake	Pass	Gauge Site	Distance (km)	Validation rms (cm)*
Ontario*	015	Rochester	20	2.95
Woods**	178	Warroad	35	12.85
Diefenbaker	043	Gardiner Bay	20	14.94
Powell	076	Glen Canyon	80	20.17
Yellowstone	143	Bridge Bay	2	33.20

*rms based on AMR (primary) or ECMWF (secondary), the GIM model, the sea state bias and the ocean-retracker range. All others based on the ECMWF and GIM models and the ice-retracker range.
**rms improves to 6.70 cm for the May to October summer period. Distance is the approximate separation of ground track and gauge site.

Validation

Comparison with Ground-based Gauge Data

Absolute validation of the altimeter height measurements can be done by comparison with ground-based gauge data that are generally considered accurate to 1 cm. In complex basins note must be made of variable surface conditions (wind and ice) and hydrological differences associated with the distance between gauge site and altimeter crossing (e.g., Lake Powell; Table 3). For high latitude lakes, measurements acquired during freeze periods should technically be rejected prior to comparison due to ice penetration effects. Time series of relative lake level variations were derived using the Birkett (1995) method for a small collection of lakes within the United States and Canada. Lake Ontario serves as an example of a large, wind-roughened lake. Lakes Diefenbaker and Powell are situated in steeply inclined terrain, presenting narrow water-crossing extents to the instrument. Lake of the Woods and Yellowstone Lake undergo seasonal freeze/thaw periods.

One satellite overpass (Table 1) and one gauge site are considered for each validation target. Lake Ontario has a number of ground-based gauges, but only data from the Rochester gauge are utilized here, being closest (~20 km) and to the southeast of the southern ground track/coastline intersection point. Because validation exercises for Ontario revealed that comparison with hourly gauge data had poorer rms values (by 0.2 to 0.4 cm) than results using mean daily gauge data, each validation exercise here utilizes the averaged-daily gauge data. Each gauge data set has its own reference datum (e.g., local, mean sea level, the International Great Lakes Datum or IGLD) but as the repeat track technique produces relative altimetric height variations, the altimeter results are simply shifted vertically to minimize the fit (Figure 8), and the corresponding rms on the height differences with respect to a mean difference are recorded (Table 3). The expected RSS of all altimetric height corrections (Table 2) has been combined with the number of available height values across the lake, along the satellite track, to estimate the relative height error bars.

Based on the ocean-retracker range, validation exercises show that in the case of Lake Ontario (Figure 8a), the application of the sea state bias (SSB) makes a significant improvement (~0.4 cm) to the rms. The use of the GIM ionospheric range correction also improves the rms by ~1.5 cm over the application of the dual-frequency ionospheric

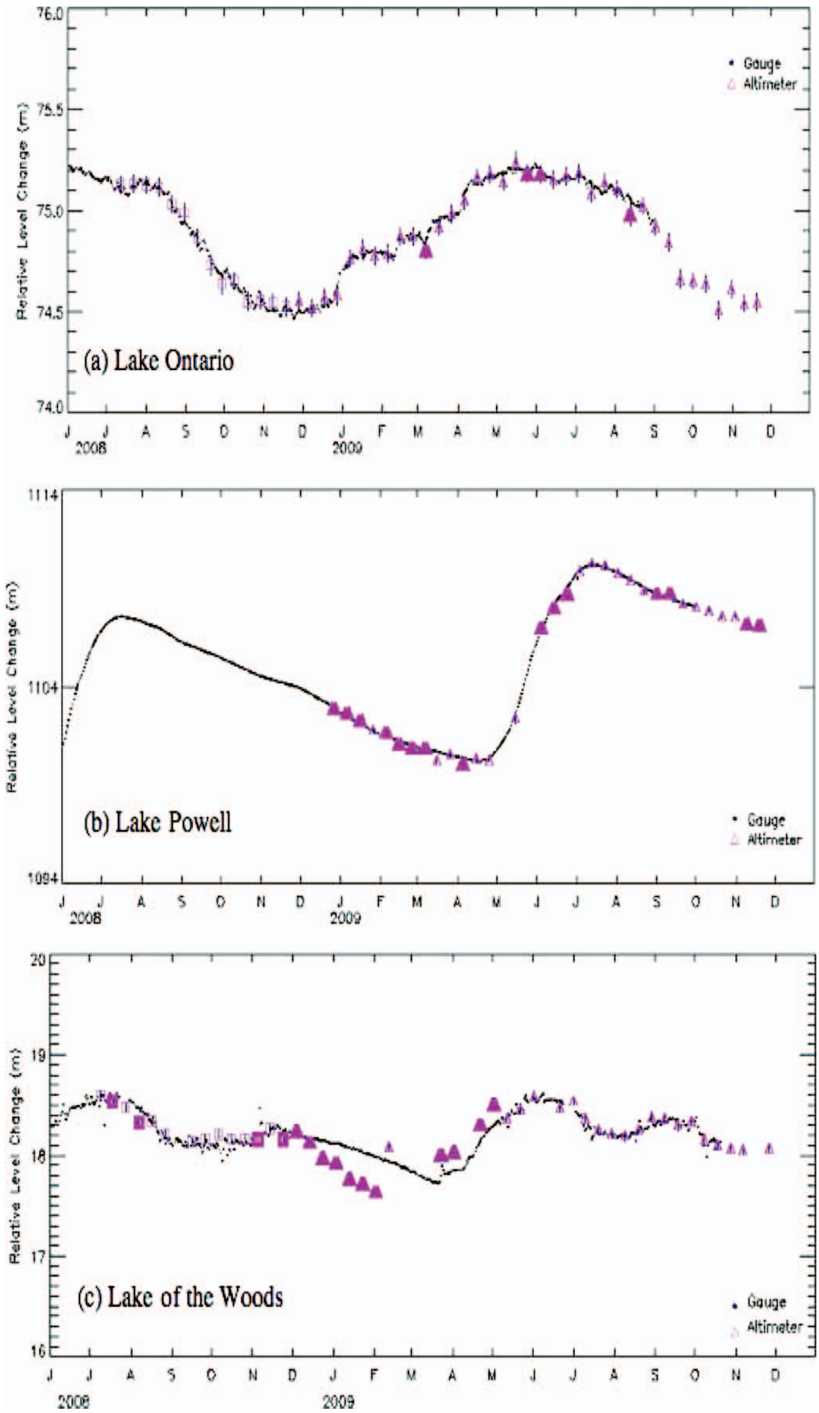

Figure 8. Absolute validation results utilizing the Birkett (1995) repeat track method. Comparing the Jason-2/OSTM elevation measurements to ground-based gauge data for **(a)** Lake Ontario, **(b)** Lake Powell, **(c)** Lake of the Woods, **(d)** Yellowstone Lake, and **(e)** Lake Diefenbaker. Radar altimeter measurements are presented as squares (version-T) and triangles (version-C) and a bold symbol indicate where the radar backscatter coefficient is ≥20 dB. Gauge data are presented as solid circles. Table 3 provides associated rms values for the synergistic altimeter/gauge measurements.

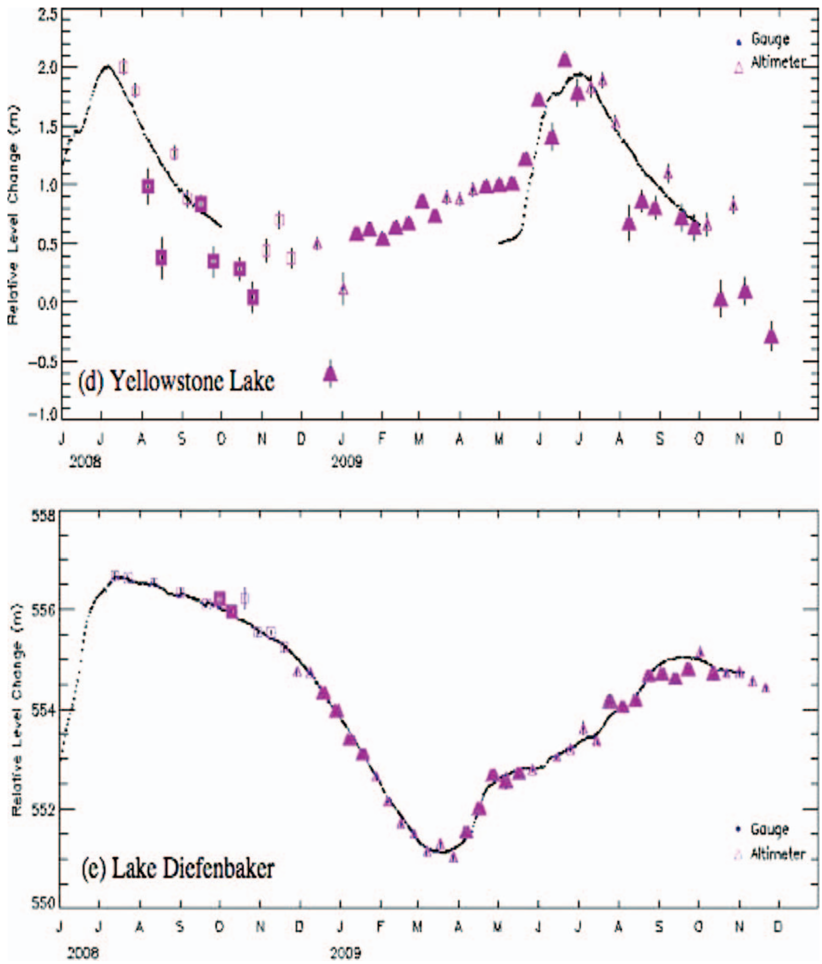

Figure 8. *(Continued).*

correction. With the GIM, SSB and AMR wet tropospheric corrections applied, a best rms of 2.95 cm is achieved, outperforming the 1-Hz estimated error in Table 2. The application of the ECMWF wet tropospheric correction degrades the rms by only 0.05 cm probably due to a good ECMWF-model accuracy in this region. Interestingly, the application of the ice-retracker range degraded the rms to 4.89 cm rms (ECMWF) and 5.36 cm rms (AMR) revealing increased variability on the range measurement for ocean-like echoes.

For the remaining lakes, setting the range corrections to ECMWF (in consideration of target size and ice) and GIM, setting SSB to zero, and selecting the ice-retracker range for enhanced acquisition and data quantity gave a variety of rms (Table 3). These values are representative of filtered time series where there has been some rejection of data points of significant error bar size (>0.25m) and/or significant deviation of the data point from a clear seasonal variation. These points can often (but not always) be the cycles pertaining to the DIODE/DEM mode, Lake Powell (Figure 8b) being the most striking case where all version-T DIODE/DEM cycles were ~10m below the expected height level. In the case of Lake of the Woods, winter altimetric measurements with large error bars or large deviation from the gauge data were initially rejected resulting in a preliminary 12.85 cm rms. Deviation between the altimeter and gauge data remains, though, due to ice penetration effects (Figure 8c). Focusing on the summer May–October periods only, a 6.7 cm rms is achieved. The rms estimate for Yellowstone Lake (33.20 cm) is based on May to September, the only months for which gauge data are available. The altimetric time series is noisy (Figure 8d), and auxiliary information suggests that "summer periods" may not be completely ice free. Many of the time series in Figure 8 depict cycles when the mean σ° is above 20 dB (bold symbols), approximately denoting periods of summer calms or winter ice conditions.

Overall, the validation exercises show good altimetric accuracy and the time series are able to capture much of the seasonal variation. The ice-present periods though still remain a problem for these radar instruments. For results where cycles 003, 005, 007, and 034 are present, no height bias was observed between the DIODE/median and DIODE/DEM tracker mode output. With refined IGDR satellite altitude and more accurate range corrections, there is a clear improvement in the Lake Ontario rms compared to the early T/P GDR and Jason-1 IGDR results (4.0–5.0 cm; Birkett 1995; McKellip et al. 2004), and these values may improve again via utilization of the GDR. The $\sim$15 cm and $\sim$20cm rms are remarkable for Lakes Diefenbaker and Powell (Figures 8e, 8b) considering the narrow extent of water and the nature of the surrounding terrain. Historical T/P validation exercises placed the Lake Powell rms at $\sim$1.6 m (Birkett et al. 2009). The Diefenbaker and Powell Jason-2/OSTM results are a merit to the acquisition, tracking, retracking and 20Hz combination of this mission.

Further studies on data filtering options and the estimation of time series error bars (including further checks on range corrections and deviations from expected seasonal variation) are ongoing. However, the validation results here can be expected for other water bodies around the world equating similarities between terrain type, surface roughness and lake size/water extent. Note that while the result for Yellowstone Lake is just outside the limit (22%), the validation exercises show that the accuracy requirement (10 cm rms for the largest lakes, 20% of the maximum seasonal amplitude for others) of the USDA/GRLM operational program is being satisfied.

Validation of the USDA/GRLM Lake Products

The creation of the GDR T/P and IGDR Jason-1 lake level products for the USDA/FAS is described in Birkett et al. (2009). With the availability of a new IGDR data set from the Jason-2/OSTM there was an opportunity to revise the original products and extend the monitoring period with Poseidon-3 measurements. The modifications included utilizing a new reference datum for the repeat track method based on a nine-year (integral number of seasons) TOPEX/Poseidon data archive. Range and height parameter corrections were also altered to i) utilize the DORIS or GIM ionospheric correction (replacing the dual-frequency option), ii) apply the loading tide correction, and iii) apply the pole tide correction multiplied by the 0.46 scaling factor. Routine weekly ingestion of the Jason-2/OSTM IGDR data began in October 2009, the Poseidon-3 products allowing the program to be in operational mode once again. The new TPJO.1 (meaning TOPEX/Poseidon, Jason-1, OSTM) products are preliminary version1 and still undergoing checks via similar absolute (ground-based gauge) and relative (between repeat track methods and between the differing radar altimeters) validation exercises. Two examples are presented here.

Based on the Birkett et al. (2009) methodology and utilizing the ocean-retracker range, comparisons of the Jason-2/OSTM portion of the GRLM product for Lake Ontario

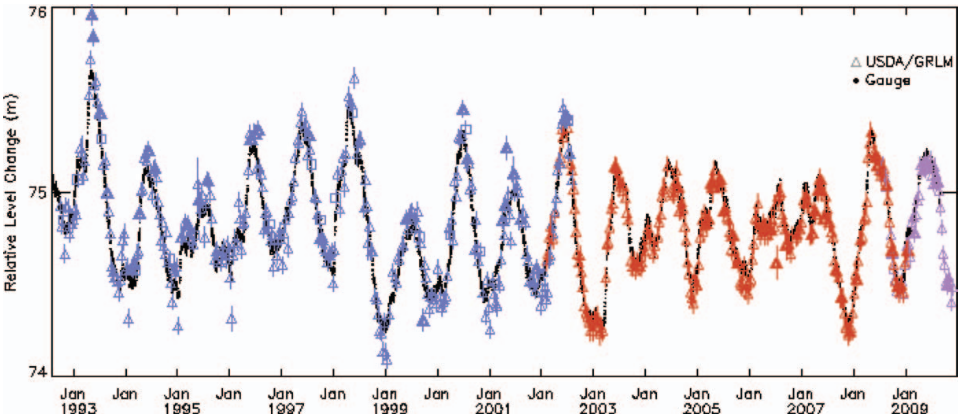

Figure 9. Absolute validation of the TPJO.1 GRLM lake product for Lake Ontario. Altimeter measurements are from TOPEX/Poseidon (blue), Jason-1 (red), and Jason-2/OSTM (purple).

against the Rochester gauge data gave an rms of 4.16 cm, which improved to 3.11 cm after removal of a few clearly erroneous data points with large (>25 cm) error bars. The 3.11 cm is comparable to the 2.95 cm result found by the Birkett (1995) method showing good agreement between the two techniques for a large lake. Using a 17 cm range bias for Jason-1 and a 25 cm range bias for Jason-2/OSTM, the combined mission product can be similarly validated. After similar filtering, the full Lake Ontario TPJO.1 product revealed an rms gauge comparison of 7.85 cm (Figure 9). This satisfies the 10cm rms USDA requirement for a multiinstrument long-term time series.

While the TPJO.1 ice-retracker output remains at the production stage for the other North American validation targets in Table 3, we can test the TPJO.1 ice-retracker output for other large lakes in a relative validation sense, by comparing output between the two repeat track methods. Figure 10 shows the time series produced by the Birkett (1995) and Birkett et al. (2009) methods for Lake Volta, using the ice-retracker range and applying the AMR (primary, ECMWF secondary) and GIM parameters, and setting SSB to zero in both

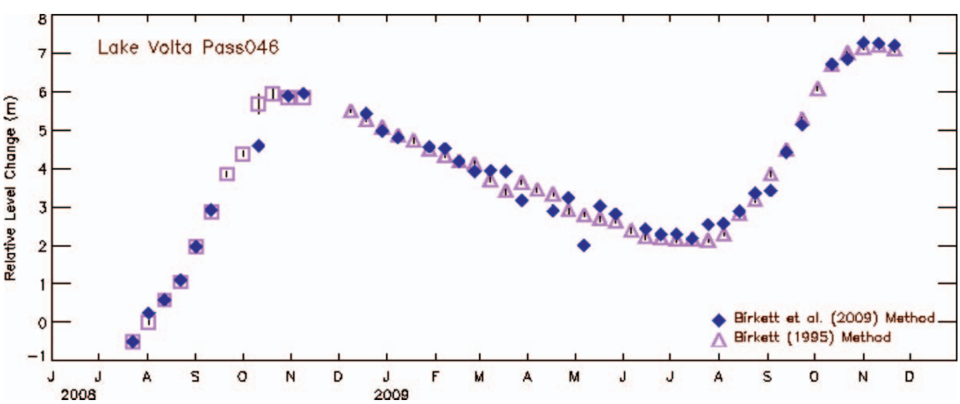

Figure 10. Relative validation exercise comparing Lake Volta time series derived using the ice-retracker range and the Birkett (1995) (squares [version-T] and triangles) and Birkett et al. (2009) (diamonds) repeat track methods.

methods. Results on the filtered time series shows an rms on the differences of ∼30 cm or ∼5% of the mean seasonal amplitude (∼6 m). While this has merit, focus remains on the potential differences in the filtering techniques between the methods, and on the 50% reduction in the number of Jason-2/OSTM 20-Hz data points being used in the Birkett et al. (2009) method due to the use of a 10-Hz T/P datum across the lake.

Conclusions and Future Research

The Poseidon-3 radar altimeter on board Jason-2/OSTM is performing well over lakes and reservoirs of varying size and surface roughness, despite the complexities of the surrounding terrains. A global set of case-study lakes and reservoirs provided a broad range of target size (150 km^2 to 380,000 km^2) and extent of water presented to the instrument (800 m to 1085 km). The targets span high and low latitudes and experience seasonal differences in water level variation ranging from 0.5 m to many meters. They also represent regions that have periods of calm, stormy, frozen or drought-prone water conditions.

Investigations utilized the interim IGDR, a data set available to users 1–3 days after satellite pass and the focus of the USDA/GRLM program that outputs near-real time altimetric lake level products. Studies of the various IGDR data quality flags show that many are not applicable to the full range of lake/reservoir sizes due to the limited 1-Hz resolution and inherent assumptions of an ocean surface response and associated echo type. Evaluating the available ionospheric range corrections also reveals that over large unfrozen lakes the dual-frequency instrument-based correction has a much higher variability. In addition, in the case of Lake Ontario the dual-frequency correction is less accurate than the GIM model. Regarding the wet tropospheric range correction, there are lakes for which the ECMWF correction has a higher humidity level (i.e., a greater negative range correction value) than the instrument-based AMR correction by amounts ranging from ∼10% (Lake Ontario) to ∼30% (Lake Chiquita). Observation of the radar backscatter coefficients associated with the ice- and ocean-retracker outputs shows a difference of ∼1 dB for wind-roughened (σ° <16 dB) surfaces where ocean-like waveforms are expected. This bias is noted to decrease with increasing σ°.

With regards to monitoring the unfrozen waters of the largest lakes and inland seas, data users might employ the 1-Hz IGDR quality and land mask flags, and the instrument-based AMR and dual-frequency, and sea state bias range corrections. For such large targets height losses near the coastlines could be acceptable. For all target-size considerations, the use of maps and satellite imagery to determine the coastline crossing locations and potential knowledge of seasonal effects will better assist target location and data interpretation. In these cases the use of the AMR (noncoastal, unfrozen waters with valid in-expected-range measurements) or ECMWF (all water surfaces) wet correction and the GIM ionospheric correction, and rejecting the application of the sea state bias, are recommended in the construction of the altimetric lake height. Observation of either of the radar backscatter coefficients (searching approximately for $\sigma^\circ \geq 20$ dB), and perhaps the 20-Hz waveform peakiness and MQE flags will assist in determining periods of calm or frozen waters. In the process, all height correction parameters should be checked against their validity range, and the expected height range and along-track height rms can be utilized as an aid to data filtering.

In a departure from the IGDR and GDR data sets of T/P and Jason-1, the Jason-2/OSTM IGDR contains two range values, the output from ocean-retracker and ice-retracker algorithms. Both are postprocessing parameters, and the latter is included in the IGDR for analysis of nonocean-like echoes. Over the various lake targets both range values can be available at a given location, but in many small-lake cases only the ice-retracker range is present. Observation shows that the majority of ice-retracker heights are biased higher (range biased lower) than those derived from the ocean-retracker. The bias is spatially and temporally variable with mean values between 17 cm (Lake Baikal) and 29 cm (Lake Ontario) and is noted to increase with decreasing σ° in the 10–16 dB range. Some range bias is to be expected due to differences in waveform interpretation and the associated physical quantity being measured. Because of this bias though, data users should not mix the differing retracker output over a given satellite pass. If both exist, the ocean-retracker range should be prioritized for lake surfaces with ocean-like waveform characteristics. For either range value, the rms of the along-track associated heights can be taken as an approximation to the range precision. This is found to be target and σ° variable, depending on wind and ice-conditions. With relevance to the ocean-retracker output, the minimum (best) rms of the 1-Hz along-track height values observed for Lakes Ontario and Woods are 3 and 6 cm, respectively. Minimum ice-retracker rms values for the same lakes are 1 and 4 cm, and for Lake Chad 12 cm. Range precision contributes to the overall error on the constructed heights but can be improved by averaging across the full extent of the lake.

To date, the default on board surface tracking logic is the combination of DIODE acquisition and median tracker, with the exception of cycles 003, 005, 007, and 034, where the experimental DIODE/DEM tracking mode was in operation. Over the majority of the case study lakes, both the DIODE/DEM and DIODE/median tracking combination do well. Based on observation of the quantity and location of the valid IGDR lake heights (the combined effect of on board surface acquisition/tracking and postprocessing retracker output), the DIODE/DEM mode cycles can consistently have the fastest lake acquisition times as the satellite passes from land to water. For some targets, though, this mode can fail to acquire the surface, or it can lose lock part way across the lake, or the acquisition times can be slower that the DIODE/median tracker combination. In addition, and with the relevance to the case study targets here, no clear advantage could be observed to the DEM upgrade in cycle 034. These results may point to the DEM not being optimized for all regions.

In several case study regions, there is also clear evidence that the fine-tuning of the instrument parameters during cycle 016 resulted in improved tracking performance with an increased number of valid elevations across the lake. Analysis of the IGDR also reveals that the DIODE/median tracker/ice-retracker output has several advantages. For this combination there is a good ability to acquire the lake surface rapidly, in several cases within 0.1 s (580 m), and the majority to within 0.4 s ($\sim$2.3 km) of the coastline. The ice-retracker also has the advantage of acquiring additional height data within the coastal waters and during periods of smooth water, that is, either during summer calms or winter freezes. Associated height profiles across the lake also have lower rms variability, and there is less range-deviation sensitivity to σ° variations. There is also the ability to monitor lakes with surface areas as small as $\sim$150 km^2 and water bodies with $\sim$800 m of along-track water extent.

For a subset of North American lakes, validation exercises utilizing the Birkett (1995) repeat track methodology show that the rms accuracy of a time series of altimetric height variations can vary between 2.95 and 33.20 cm when compared to ground-based gauge data. In some cases, such as Lake Powell, there is much improvement over historical results. In the case of Lake Ontario, investigations showed that improvements to the rms could be achieved via the application of the sea state bias ($\sim$0.4 cm) and the GIM ionospheric correction ($\sim$1.5 cm, compared to its dual-frequency counterpart). The AMR wet tropospheric correction only improved the rms by 0.05 cm probably reflecting the good accuracy of the ECMWF model input data in this region. The use of the ice-retracker range, however, degraded the rms by at least 2 cm. While the Lake Ontario result (derived using the ocean-retracker range) gave the best rms of 2.95 cm, the other lakes (ice-retracker) were poorer, but they were specifically chosen to reflect a range of problems associated with the global observation of a wide-variety of lakes. For example, the accuracy is clearly degraded when encountering problems due to a narrow water extent ($\sim$10 km Lake Diefenbaker with rms 14.94 cm, $\sim$800 m Lake Powell with rms 20.17 cm) and when encountering ice penetration effects (12.85 and 33.20 cm for Lake of the Woods and Yellowstone Lake). Based on the validation exercises, no systematic bias in height measurement could be observed between the DIODE/DEM and DIODE/median tracker mode cycles.

The Jason-2/OSTM results within the USDA/GRLM lake product for Lake Ontario and derived using the Birkett et al. (2009) methodology were found to have a gauge V altimeter rms of 3.11 cm. This is comparable with the 2.95 cm, cross-validating the two methods that utilize different reference datum approaches. Furthermore, utilizing a range bias of 17 cm (Jason-1) and 25 cm (Jason-2/OSTM) the full TPJO.1 GRLM product for Lake Ontario has a gauge comparison rms of 7.95 cm, well within the USDA requirements. In the absence of gauge data, a relative validation check on the Jason-2/OSTM portion of the GRLM product for Lake Volta (ice-retracker) revealed a 30 cm rms variation between the Birkett (1995) and Birkett et al. (2009) methodologies. Although this is well within the USDA requirement of being $<5\%$ of the seasonal amplitude, further investigations into differences in data filtering methods and reference datum, as well as ocean- versus ice-retracker output is required. Overall though, all of the validation results show accuracies that are acceptable and an improvement over historical values (e.g., T/P and Jason-1 over Lake Ontario 4–5 cm rms; Birkett 1995; McKellip et al. 2004). This is due to an improved IGDR orbit and AMR correction and an increased quantity of height measurements. The Jason-2/OSTM results presented here should translate to other lakes around the world of comparable size, terrain, and surface roughness.

The success of the Poseidon-3 instrument over lakes and reservoirs is primarily due to the new DIODE acquisition mode that utilizes the real time on-board estimation of the satellite altitude for the range determination. Target surfaces can be more quickly located than in the historical autonomous modes of T/P and Jason-1. The median tracking mode, similar to that used on board ENVISAT and T/P, also assists in maintaining lock across highly variable lake surfaces. The availability of the postprocessed ice-retracker range within the IGDR data set is a valuable and additional bonus, relocating the surfaces of many regions where the waveforms deviate from ocean-like. While observation of the ocean-retracker heights shows improvement in data quantity over the historical NASA/CNES missions, it is with access to this IGDR ice-retracker output at 20-Hz that users will find the Poseidon-3 data far superior to the equivalent T/P and Jason-1 records. In this respect the Jason-2/OSTM will be able to successfully monitor smaller lakes and reservoirs, providing input to the USA/GRLM and science programs, and become an additional data source to validate the new expected products from the synergistic ENVISAT mission and the Indian Space Research Organization (ISRO)/CNES SARAL mission, which is expected to launch in 2010.

Based on the research here some data set modifications are proposed, and it is worthy to note some outstanding problems relating to lake/reservoir monitoring in general. Based on the interim data set observation, we recommend that the IGDR version-T data set (cycles 000–014) be upgraded to version-C to increase data quantity for some lakes and enable uniformity of measurements across all cycles. The inclusion of a 20-Hz ice-retracker validity flag and tracking mode flag would also assist analysis. Because of the invalidity of some of the quality flags, the problem of identifying heavy rain events and of rejecting erroneous height data during freezing periods remains with the Jason-2/OSTM data set as it does for other radar altimeters. The monitoring capability of all of these profiling instruments is not global, and results for the smaller lakes and reservoirs are still dependent on a model-based ECMWF wet tropospheric range correction. This correction may contribute a large error and further investigation into the validity of the current AMR correction and into the new research-grade AMR enhanced products (with improved rms up to the coastlines, Brown 2010) will be undertaken. The advent of satellite-based laser altimetry with negligible ice penetration effects might assist with lake monitoring capability during winter periods. Users currently have the opportunity of exploring the laser altimeter data from the Ice, Cloud, and Land Elevation Satellite's Geoscience Laser Altimeter System (ICESat/GLAS) instrument in this respect and look to the future launches of the NASA ICESat-2 and DESDynI missions. The proposed NASA SWOT mission, based on wide-swath radar interferometry techniques, will also attain a more global perspective, having the potential capability to monitor surface heights of lakes, as well as river widths and surface gradients (Fu 2003; NRC 2007).

In the meantime, the focus is on further performance checks with additional test-case lakes. These will include a greater number of small targets (100–300km^2), more large and open bodies of calm water, and regions where the satellite skims the edges of the lake. To test the limits of monitoring capability, ephemeral and reservoir targets where seasonal level variation is minimal (<0.5 m) will also be studied. For all cases the ice/ocean-retracker range bias will be revisited and their differences with respect to gauge validations investigated. The use of the S-IGDR data set will assist here and allow further investigations into waveform characteristics and retracker options. In this regards emphasis will also be on investigating the retracker options and Jason-2/OSTM data output from the CNES Prototype Innovant de Système de Traitement pour I'Altimétrie Côtière et I'Hydrologie (PISTACH) program (see appendix). Analysis of the GDR data set (with the precise satellite orbit and improved AMR correction) will reveal improvements in accuracy compared to the IGDR results and allow a search for any difference in data quantity to the IGDR version-T and version-C. Working with the Jason-2/OSTM SWT, the DIODE/DEM and DIODE/median tracker modes will additionally be investigated to assess the reasons for full or partial data loss over several of the high altitude and island lakes. Future DEM revisions may also require testing. With regards to the USDA operational monitoring program, differences between the Birkett (1995) and Birkett et al. (2009) repeat track methods will undergo further analysis and additional TPJO.1 products validated. In all such exercises, relative-validation checks will also utilize the ESA and LEGOS operational based lake products as well as GRLM results from the ENVISAT and SARAL missions.

Acknowledgements

The authors thank the reviewers for valuable comments on the manuscript. The authors acknowledge AVISO (through CNES) for the provision of the Jason-2/OSTM IGDR data set. The following are acknowledged for the lake/reservoir gauge data: NOAA (Lake Ontario), the USGS (Lake of the Woods), the U.S. Bureau of Reclamation (Lake Powell), the USGS/NPS/Boat Concessionaire/Phil Farnes (Yellowstone Lake), and Environment Canada (Lake Diefenbaker). Satellite image access is courtesy of 2009 Google Earth software and Maps service. This research was funded by the NASA OSTM (NNX08AT88G) and NASA Decision Support (NNX08AM72G) grants.

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Appendix

Information on public access to the Jason-2/OSTM satellite data through NOAA or AVISO can be found at http://www.aviso.oceanobs.com/en/news-storage/news-detail/index.html?tx_ttnews%5Btt_news%5D = 562&tx_ttnews%5BbackPid%5D=285&cHash=c7c571f718

Details of the PISTACH Experimental Coastal and Hydrology products can be found at http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/coastal-and-hydrological-products/index.html

Lake Level Products can be acquired through the USDA, ESA, and LEGOS programs at:

http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/index.cfm
http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main
http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/